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U.S. Access to Space

Launch Vehicle Choices for 1990–2010

Scott Pace

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Studies of space transportation in recent years have spanned a wide range of issues, from the pressing problems of recovering from specific failures and meeting budget limits to how the U.S. space program might develop over the next 50 years. However, there have been few studies that compare both means and ends. This report evaluates launch vehicle combinations capable of meeting a range of U.S. space traffic needs between 1990 and 2010. The evaluation aims to clarify alternatives available to the United States in pursuing potential national goals and to increase understanding of the implications of those alternatives. The study methodology involved six steps: (1) review the space transportation planning process, current issues, and political factors; (2) define alternative levels of U.S. space traffic demand for 1990-2010; (3) create various combinations of existing and proposed launch vehicles to fulfill each demand level; (4) calculate costs and uncertainties; (5) interview space transportation planners on institutional criteria for evaluating launch vehicle mixes; and (6) evaluate launch vehicle options and recommend preferred U.S. actions in space transportation planning and procurement.

PREFACE

The examination in this report of the choices facing the United States government in providing access to space was undertaken as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Public Policy Analysis from the RAND Graduate School. Support was provided by the Technology Applications Program within Project AIR FORCE.

The data used in this work are from publicly available materials. The evaluation of alternative choices in space transportation should be of interest to the Office of the Secretary of the Air Force, particularly SAF/OSN and SAF/AQS; Air Staff Plans and Operations (XO); Studies and Analyses (SA); Programs and Resources (PR); the U.S. Space Command; and the USAF Space Command. In addition, this work may be of interest to the National Aeronautics and Space Administration, the Office of Management and Budget, and Congressional staffs with responsibility for space transportation planning.

The cutoff date for data in this report is March 1989.

SUMMARY

INTRODUCTION

In the aftermath of a string of launch vehicle disasters in 1986, the United States has made major changes in its usage of launch vehicles. New expendable launch vehicles (ELVs) have been procured and space shuttle flight rates have been reduced. Payloads have been delayed, cancelled, or shifted to different vehicles. The transition to a mixed fleet of shuttles and ELVs, the emergence of a commercial launch industry, and proposals to build a heavy-lift launch vehicle have characterized this turbulent period in U.S. space transportation.

Studies of space transportation in recent years have spanned a wide spectrum. At one end, the United States has concentrated on meeting the pressing problems of recovering from specific failures and meeting budget limits. At the other end, there have been visionary studies of where and how the U.S. space program might develop over the next 50 years. Largely missing, however, have been studies combining a comparison of both means and ends. Such studies would bridge the gap between current problems and the longer term goals that depend on U.S. policy choices. For example, if the United States chooses to pursue space goals with requirements for space transportation, what is the best way to meet that transportation demand?

APPROACH

Over the next two decades, the United States will need to provide access to space under severe resource constraints. Decisions are needed not only on the goals of U.S. space efforts, but on how to best meet derived requirements for space transportation. This report evaluates launch vehicle combinations capable of meeting a range of U.S. space traffic needs between 1990 and 2010. The purpose of the evaluation is to clarify alternatives available to the United States in pursuing potential national goals and to increase understanding of the implications of those alternatives.

The methodology for this study involved six steps:

1. Review the space transportation planning process, current issues, and political factors affecting analyses (Sec. II and App. G).
2. Define alternative levels of U.S. space traffic demand for 1990–2010. Each demand level assumes a notional set of U.S. goals to be met (Sec. III and App. A).
3. Create differing combinations of existing and proposed launch vehicles to fulfill each demand level (Sec. IV).
4. Calculate costs and uncertainties (e.g., payload losses and standdown times) associated with each launch vehicle combination (Sec. IV and Apps. B–D).
5. Interview senior space transportation planners and decisionmakers on differing institutional criteria for evaluating launch vehicle mixes (Sec. V and App. F).
6. Evaluate launch vehicle options and recommend preferred U.S. actions in space transportation planning and procurement (Secs. VI and VII).

No recommendations are made as to which goals the United States should pursue in space. Rather, recommendations on launch vehicle choices are made for cases where future space traffic is given (a policy choice has been made) and for cases where it is uncertain (where policy choices are deferred).

The central theme that runs through both the internal debates and the external conflicts among space transportation planners and decisionmakers is the issue of *why launch vehicles are built*. One view advanced by both DoD and NASA transportation planners argues that launch vehicles shape the types of payloads launched by the United States and thus vehicles should be designed in anticipation of future needs. This "proactive" view is sometimes taken further in arguing that the creation of launch vehicles should be used as a tool to shape the traffic demand. Some proponents argue that their new vehicles will not only reduce launch costs, but more generous payload volumes and frequent flights will help lower the payload costs which now dominate space system costs.

The alternative view might be labeled "reactive" in that it sees launch vehicles as being built only after approved payloads exist. Launch vehicles are nothing more than means to an end, a way of placing a particular object in space in the service of the national interest. Proponents insist that strict attention to known launch requirements is necessary to justify vehicle procurements and to avoid wasting resources.

The conflict of proactive and reactive views is important in shaping the nature and justification of proposed launch vehicles. The former view will often press for new technological or operational breakthroughs while the latter will seek to evolve known systems to meet future needs. The proactive view promises high reward for greater risks and uncertainties while reactive views seek to minimize both risk and uncertainty. These characteristics often lead to debates in which both sides talk not so much to each other as to their adherents.

INSTITUTIONAL PERSPECTIVES ON SPACE TRANSPORTATION PLANNING

Interviews were conducted within the Department of Defense, NASA, the Congress, and the Executive Office of the President on institutional perspectives affecting launch vehicle planning and procurement, the likelihood of differing levels of space traffic, and the uncertainties affecting their decisions. One purpose of this process was to identify areas of consensus and uncertainty among decisionmakers to define a basis for negotiations in implementing launch vehicle decisions.

Despite wide variations in individual perceptions of space transportation priorities, a significant degree of consensus existed on broad policy issues among those interviewed. For the national security sector, few senior planners expected that space-based strategic defenses would be deployed in the next 10–15 years. For the civil sector, it was expected that the United States would maintain a commitment to manned access to space—with or without the space station. For the commercial sector, all planners expected that the United States would seek to promote a commercial launch vehicle industry and maintain a mixed fleet of vehicles.

These areas of policy consensus are matched by a consensus on what the United States will likely do in the near-term in its inventory of launch vehicles. This view is driven not so much by policy agreement, but rather by universal recognition of near-term budgetary pressures. Shuttle flights will continue, although possibly not at the levels that NASA is now projecting. The government will continue to buy expendable launch vehicles, or at least their services. This will continue until other alternatives become available such as an operational family of Advanced Launch System (ALS) vehicles. Even then, future upgrades of ELVs might themselves become the ALS family of vehicles.

Between the vision of national policy goals and the inertia of current programs are the following planning questions:

- Should the United States purchase more ELVs to support national security and civil space goals?
- Should the United States build a Shuttle-C?

- Should the United States continue the ALS program without either a commitment to deploying strategic defenses or expanding civil space efforts?
- How should the United States plan for manned access to space beyond the space shuttle?

Each of these questions reflects political and technical uncertainties, and thus areas of major disagreement within the space transportation planning community. These issues are addressed in the following evaluation of U.S. launch vehicle alternatives and in the Conclusions and Recommendations subsections.

SPACE TRAFFIC DEMANDS AND ALTERNATIVE LAUNCH VEHICLES

In order to evaluate the launch vehicle options available to the United States, a definition was required of what the United States can and is likely to achieve in space transportation over the next two decades. Four space traffic demand levels (combining both shuttle and ELV flights) were created:

- Constrained demand: total U.S. launch rates of about 10–15 equivalent shuttle flights per year.
- Nominal demand: total flight rates of about 20–30 equivalent shuttle flights per year, rising to about 60 by 2010.
- Expanded civil space program: peak flight rates of 35–70 equivalent shuttle flights per year.
- Expanded DoD demand (e.g., Strategic Defense Initiative [SDI] deployment): a steady rise to 120–140 equivalent shuttle flights by 2010.

Seven launch vehicle mixes were examined for each baseline demand level. These mixes were:

- Current Space Transportation System (STS/ELV) usage plans as a base for all options
- Adding more ELVs
- More ELVs and a five-orbiter shuttle fleet
- Adding a Shuttle-C
- Adding an ALS heavy-lift vehicle (HLV)
- Adding a Shuttle-C and ALS HLV
- Adding a low-flight-rate ALS HLV

The launch vehicle mixes were not applicable to all demand levels as there was usually a large undercapacity or overcapacity. Some modifications were defined to bring applicable mixes closer in line with the baseline demands.

There are many complex issues of cost, risk, performance, and programmatic tradeoffs associated with alternative U.S. launch vehicle mixes. Cost estimates were made for launch vehicle mixes capable of meeting each of the four traffic demand projections. (See Sec. 4.4.) Separate estimates were then made of risks for each alternative mix due to launch vehicle reliability and standdown delays. (See Sec. 4.5.) Finally, estimates were made of the budgetary growth required to support each applicable combination of launch vehicles and payloads for the four demand projections. (See Sec. 4.4.)

Table S.1 summarizes key features of the launch vehicle mixes found to be applicable to the four defined demand levels. The estimated launch vehicle cost to meet the 1988 manifest, of both civil and military payloads, was $36 billion. This included launches through 1995. Cost estimates for launch vehicles from 1988 to 2010 each contained the $36

billion figure for the 1988–1995 period. Expected payload losses were based on estimates of reliabilities and payload capacities of each vehicle in the mix. Average payload costs were assumed to be about $10,000 per pound to arrive at estimates of total required budget growth rates for both vehicles and payloads. (See Sec. 4.3 and Apps. D.2 and D.3.) This figure is on the optimistic side and should thus be taken as largely a lower bound for payload costs.

Table S.1

SUMMARY OF ALTERNATIVE LAUNCH VEHICLE MIXES, 1988–2010

Option		Launch Vehicle Costs (1988 $)	Average Launch Cost per Payload Pound (1988 $)	Expected Total Losses (STS Equivalents) 1966–2010 (Percent)
0	Manifest 1988–1995	$ 36 billion	$5300	
	Constrained demand			
1	STS/ELVs	$ 79 billion	$5500	1.6
2	All STS after 1995	$ 82 billion	$5700	0.6
3	All ELVs after 1995	$ 70 billion	$4900	2.7
	Nominal demand			
4	Current STS/ELVs	$114 billion	$5400	2.7
5	Plus more ELVs	$118 billion	$5600	3.1
6	*Or add Shuttle-C*	$131 billion	$6300	2.9
	Expanded civil demand			
7	Low rate ALS HLV	$128 billion	$4400	1.9
8	ALS HLV and Shuttle-C	$142 billion	$4900	2.0
	Expanded DoD demand			
9	High rate ALS HLV	$144 billion	$2100	2.2
10	ALS HLV and Shuttle-C	$159 billion	$2300	2.2

Budget growth rates for launch vehicles and payloads:

Constrained demand	–0.16 to 1.0% per year
Nominal demand	2.0 to 2.3% per year
Expanded civil demand	About 5% per year
Expanded DoD demand	About 8.8% per year

EVALUATION OF LAUNCH VEHICLE OPTIONS

To recommend what combination of launch vehicles the United States should pursue, evaluation criteria were selected (see Sec. 5.1) and then refined in discussions with space transportation planners and decisionmakers. For each demand level, applicable launch vehicle mixes were evaluated in terms of each evaluation criteria category:

- Performance—launch mix capacity and flexibility
- Cost—recurring and nonrecurring costs
- Operational risk—payload losses and delays
- Programmatic risk—development delays and overruns
- Mission requirements—requirements for specific missions

In the case of constrained demand, the capacity of each option is approximately the same, with the STS/ELV option providing greater flexibility in being able to perform both manned and unmanned missions. Using only unmanned ELVs would be the least expensive option, whereas using only the shuttle would be the most expensive. However, ELVs are likely to still be less reliable than the shuttle and will suffer a greater degree of payload losses and delays. All of these launch vehicle options use existing vehicles, so programmatic risk concerns for new developments are not applicable. Finally, the mission requirements category notes that some manned missions could not be flown with ELVs, whereas other missions are most appropriate on ELVs. Thus the continuation of a mixed fleet of shuttle and ELVs is preferred even for a very constrained demand level.

In the case of nominal demand, the addition of Shuttle-C flights creates the greatest amount of capacity, whereas maintaining only the current levels of STS and ELV flights leaves some demand unmet. The Shuttle-C also is the most costly option, and it is unclear whether all of its capacity would be used. The addition of more ELVs provides the most flexibility, but at the risk of larger payload losses and delays. Since the Shuttle-C requires some new development, it carries more programmatic risks than options using only existing vehicles. The most difficult question is whether there are specific mission requirements for the Shuttle-C that would justify its development.

In the case of expanded civil demand (such as a return to the Moon or manned Mars missions), new vehicles would be required in addition to shuttle and ELV flights. Adding an ALS heavy-lift vehicle (ALS-HLV), or a combination of Shuttle-C and ALS flights, could provide similar levels of capability to meet the demand. Developing both an ALS and Shuttle-C is the more expensive option, with comparable levels of operational risk in terms of payload losses and delays. Developing only the ALS is more risky than including a Shuttle-C as setbacks in the ALS program would leave some demand unmet. The Shuttle-C uses current technologies and familiar operations and thus could be an early alternative for heavy-lift missions.

In the case of an expanded DoD demand, the launch vehicle alternatives are the same as for the expanded civil demand case. The comparisons are also the same for each evaluation category. Again, developing the ALS HLV alone is more economical than also developing a Shuttle-C, provided the ALS is successful. The Shuttle-C could, however, provide an earlier heavy-lift capability should mission requirements dictate.

CONCLUSIONS

In the event of a *constrained demand level*, the preferred option would be to cut back on the number of both STS and ELV flights, but maintain both capabilities. While it might be argued that the "all-ELV" option is cheaper, the mix of STS and ELVs is preferred in maintaining a policy of some manned access to space.

In the event of a *nominal demand level*, the preferred option is to use a four-orbiter shuttle fleet and ELVs. Additional ELVs can be bought for temporary periods of increased demand, adding important flexibility. The diversity of STS and ELV mixes would ensure the United States had at least some access to space in the event of future accidents and standdowns. The Shuttle-C was rejected as being too expensive for routine transportation. It might be procured, however, if there were some special operational benefit, such as deploying space station elements, that would justify it on noncost grounds. As the space station deployment date slips, the Shuttle-C begins to come into competition with early ALS flights. In the nominal case, however, there is not yet an overlap of the two systems.

For the case of *expanded civil demand*, the preferred option for the United States is to retain current STS and ELV usage rates and add an ALS flying at a modest rate. The Shuttle-C is still too expensive to operate, save in the case of unique operational benefits. For the case of *expanded military demand*, an aggressive ALS effort would be required and

again Shuttle-C would not play a role. The ALS would be added to current procurements of ELVs and shuttle flights. In both expanded demand options it is important to have lower costs and better operability (e.g., high reliability, shorter standdowns) over current launch vehicles. If current payload costs continue, such operability concerns are as important, if not more so, than launch costs in their impact on total space system costs.

In the event the United States is uncertain as to what demand level will transpire, shuttle and ELV flights should be procured as short-term demand levels dictate. *The ALS technology development should be supported until a decision is made on whether or not expanded demand levels will materialize.* Full-scale development of ALS vehicles will require expanded demand levels or major improvements in cost-effectiveness over current launch systems to justify its nonrecurring costs. Lacking expanded demand levels, ALS technologies might be incorporated in improving the operation of current ELVs. *The key issue for the case of uncertain demand is whether the United States needs a heavy-lift vehicle, and that decision can be delayed until the early 1990s.* A decision would be needed by 1992 for an aggressive ALS effort, and by 1993 for a modest rate ALS. At the constrained level, a heavy-lift vehicle is not likely to be needed.

The uncertainties confronting the United States are primarily a result of political indecision and the failure of the space policy community to forge a consensus on its goals; technical and programmatic uncertainties are of secondary importance. This does not mean budgetary constraints and technical obstacles are not important, but that political uncertainty exacerbates already difficult choices. Uncertainty over support for a space station leads to NASA indecision on Shuttle-C. Uncertainty over the future of the Department of Defense in space will lead to continuing current ELVs indefinitely. Both conditions make it difficult for NASA and the Department of Defense to negotiate with each other and present common recommendations to the Congress.

RECOMMENDATIONS FOR THE FUTURE

The shuttle and ELVs in a mixed fleet can and should provide the backbone of U.S. access to space in the next decade. Decisions to develop a heavy-lift vehicle should be deferred for several years until their technical benefits become more compelling or until national needs (such as increased traffic demands) emerge for their adoption.

The Shuttle-C is not desirable for any of the baseline traffic demands. However, it may be justified if it sufficiently reduces the number of shuttle flights, assembly time, and associated costs and risks of the space station program. As an institution, NASA has not been able to definitively balance the potential technical benefits of the Shuttle-C with the political costs of further increases to the space station's budget. *An independent assessment of the Shuttle-C program should be conducted soon and a recommendation made to the Bush Administration on whether to proceed to full scale development, depending on the schedule of the space station program.* This is the most pressing question for the near-term as the vehicle's probable utility fades beyond the 1990s, assuming ALS technology developments proceed. Failure to fully evaluate the Shuttle-C in the context of the space station program may result in that program bearing unnecessary costs and risks for shorter-term savings.

Lacking consensus on long-range demand levels, the United States should engage in evolutionary improvements in existing systems while supporting technology research in new launch systems. *ALS technology efforts should be supported while incremental improvements are made in the capabilities of the shuttle and ELV fleets. The technical and cost benefits of the ALS program are not yet sufficient to justify a commitment to a new full-scale development program.* Technology programs are less costly than development programs and can be continued more easily during periods of budgetary stringency. Their importance lies in providing options for transitioning to development programs as economic and technical opportunities become available.

Without major increases in space traffic demand, the United States should create a new launch vehicle line only when quantum improvements in cost-effectiveness and/or new capabilities become available. This is necessary in justifying the considerable development costs of new systems. If shuttle replacements are required before 2010, due to accidents or accelerated wear-out, their definition will depend on research results from several technology efforts, as well as shuttle operating experience. It is premature to say now how far research efforts will have progressed when a decision is required.

The claims of the proactive school on the effects of launch vehicles on payloads do not have to be accepted in toto to see the benefits of future launch systems. Similarly, the concerns of the reactive school should not be taken so literally that opportunities are missed because of a lack of vision on how to exploit new capabilities. *The key is to require a clear separation between operations-oriented and research-oriented launch vehicle programs, and a political commitment to space access without specific payloads in hand.*

This recommendation places bounds on the range of debate for the proactive and reactive viewpoints. Research programs attempting to advance launch technology need to avoid raising expectations so high as to confuse their goals with the operational realities of existing programs. A commitment to space access is required, however, to sustain the research programs which create new capabilities and improvements to current systems. Lack of such a commitment prolongs the uncertainties which have beset space transportation planning, to the detriment of the U.S. role in space.

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This report has grown out of a long-standing interest in both space activity and the conduct of major research and acquisition programs by the United States. I have been fortunate in being able to indulge this interest at length within the RAND Graduate School. I would like to thank my committee chairman, George Donohue, for his support and encouragement. He and other committee members, Elwyn Harris, Rob Lempert, and James Bonomo, provided constructive criticism, persistent encouragement, and financial support. Jean Khan provided rapid, conscientious secretarial service throughout my time at RAND, which was greatly appreciated.

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While many of the persons interviewed during this study must remain anonymous, there are a few key persons I would like to publicly acknowledge: Richard Dal Bello, Courtney Stadd, John Logsdon, and David Moore each provided crucial insights into the government planning process for space transportation for which I am indebted. Volunteer work with the National Space Society provided many opportunities to meet with key members of government and industry which facilitated the interview process.

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FIGURES

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GLOSSARY

airborne support equipment (ASE): Items flown with a satellite in a launch vehicle's payload volume which provide support services to the satellite during vehicle flight.

amortize: Generally, to spread fixed costs over a number of production units. Amortized costs may or may not be recovered from unit sales.

availability: The probability that a launch system will be operational at any given time.

average cost per flight: The total cost of a launch system divided by the total number of flights accomplished or planned.

backlog: The payloads to be flown after a launch system standdown. The backlog consists of payloads that miss their flight dates during the standdown, as well as payloads that arrive during the recovery period.

balking: The removal of payloads from a queue waiting for flight. Removal may occur due to the payload's cancellation or its assignment to an alternative launch vehicle.

code S: The NASA Headquarters Office of the Space Station.

code M: The NASA Headquarters Office of Space Flight.

constant dollars: Dollar values from different years corrected to a common base year. In this report, all dollar values are given for 1988 unless otherwise noted.

cumulative mass: Total mass placed in orbit by a particular launch system over time.

design, development, test and evaluation (DDT&E): The program phase just preceding production of a new launch vehicle. It follows the definition of mission requirements and development of preliminary vehicle concepts.

discount rate: The rate at which future cost or income streams are reduced to correct for the time value of money. Aside from inflation, future dollars are worth less than current dollars to a degree set by the appropriate discount rate.

dry weight: Weight of a satellite or launch vehicle without any fluids such as propellants or coolants.

downweight: Payload mass brought back to Earth from space.

equivalent shuttle flight: The payload capacity represented by one shuttle flight. Nominal capacity is defined as 55,500 lb and actual capacity is defined as 41,500 lb. The latter figure includes corrections for manifesting margin.

expendable launch vehicle (ELV): A launch vehicle which is used only once. All U.S. launch vehicles to date, except the space shuttle, have been ELVs.

geosynchronous orbit: Orbit at an altitude of 19,320 nautical miles and 0 degrees inclination, having a period of 24 hours.

heavy-lift launch vehicle (HLV): A launch vehicle capable of placing 100,000 lb or more of payload into low Earth orbit at one time.

inclination: The angle between the plane of a satellite's orbit and the plane of the Earth's equator.

inelastic: Descriptive for situations where relatively large changes in a good's price produce only a small change in its demand.

launch cost per pound: The cost to place one pound of payload into a reference orbit. This is usually calculated by dividing the payload capacity of a launch vehicle by its cost per flight.

learning curve: The effect of production and operations costs declining with time as experience is gained.

life-cycle cost (LCC): The total cost of a system over its entire life. This can include research and development, production, modification, transportation, introduction into an inventory, associated facilities, operations, support, maintenance, disposal, and any salvage revenue.

manifest: A schedule of launch vehicles and payloads to be flown. Both payloads and launch vehicles must either exist or be under construction to be assigned to an actual manifest.

manifest margin: The percent of a launch vehicle's payload capacity not occupied by payload. This can be due to payload packing limitations, safety constraints, or incompatibilities in the orbital requirements of the available payloads. Subtracting the manifest margin from 100 percent gives the launch vehicle's load factor.

marginal cost per flight: The cost of adding one additional flight to a launch schedule.

mission (DoD): Used in referring to individual military flights. The Department of Defense definition of "mission" can also mean a general purposeful activity, such as surveillance, that may be performed by space systems. DoD missions are derived from ongoing national security requirements.

mission (NASA): Used to refer to specific flights which may or may not be part of a larger effort. For example, the Viking mission to Mars was part of a larger program of planetary exploration.

mission model: Generally synonymous with projections of space traffic demand. The term is also used to refer to specific schedules of payload flights. A manifest is a special, near-term type of mission model that is a schedule of both payloads and assigned launch vehicles.

mixed fleet: Generally, a launch vehicle fleet consisting of more than one type of launcher. Also used to refer to a mix of reusable shuttle and expendable launch vehicles.

multiple manifesting: The allocation of more than one satellite to a single launch vehicle.

nonrecurring costs: Fixed costs, such as for DDT&E and production tooling, which are generally independent of the quantity of items to be produced or tested.

OMB functions and subfunctions: Organizational structu. for the federal budget used by the Office of Management and Budget. The functional structure is set according to the primary purpose of each budgetary activity, disregarding agency and organizational distinctions to the extent feasible. Individual programs are at a level below subfunctions.

104% rated SSMEs: Space Shuttle Main Engines which have been upgraded to provide 4 percent more thrust than the baseline design. This is the standard engine rating as of 1988. Achieving higher thrust is a subject of ongoing engine performance studies.

on-orbit: The condition of a satellite or spacecraft being in a stable orbit.

operations and support (O&S): The program phase during which a launch system is operated. It generally parallels the production of expendable launch vehicles, and follows the production of reusable launch vehicles.

orbital maneuvering vehicle (OMV): An unmanned vehicle designed for space operations such as the servicing, retrieval, repair, and orbital adjustment of satellites.

payload interfaces: The structural and electronic links between a satellite, its support equipment, and the launch vehicle.

payload weight: Mass of all material carried in the payload volume of a launch vehicle, including satellites, upper stages, ASE, and associated fluids. Payload weight may consist of both upweight and downweight masses.

polar orbits: Satellite orbits that pass over or near the Earth's poles at inclinations of around 90 degrees.

proactive view: For the purposes of this report, an opinion that launch vehicle design can and should be used to influence the design of payloads.

programmatic risk: Risk that a development program, such as for a new launch vehicle, will experience cost overruns, schedule slippage, or performance shortfalls.

reactive view: For the purposes of this report, an opinion that launch vehicles should be developed or procured only when specific payloads are known to require transportation to space.

recovery period: The time after a launch system standdown, during which flights have resumed, but before the payload backlog has been eliminated.

recurring costs: Repetitive costs incurred for each item (e.g., a launch).

reference orbit: Defined orbital altitude and inclination used as a basis for calculating vehicle performance and cost. A typical reference orbit is 100 nautical miles at a 28.5 degree inclination. Polar orbits are another common type of reference orbit.

reliability: The probability of an individual launch vehicle performing successfully.

resiliency: Generally defined as the ability of a launch system to recover from accidents and standdowns. It also refers to the probability of a second launch system accident and standdown during a recovery period.

satellite weight: *The weight of specific satellites* after launch and final orbital insertion.

space transportation system (STS): Commonly known as the space shuttle.

space transfer vehicle (STV): Also known previously as the orbital transfer vehicle (OTV), this is an unmanned vehicle that performs the function of an upper stage, but is reusable.

standdown: The cessation of launch vehicle flights after a major accident or discovery of a flight hazard in the vehicle. The length of the standdown is called the downtime.

strap-on booster: Solid or liquid propellant rocket used to provide additional thrust to a vehicle during launch.

STS equivalent month: A one-month time period for a payload mass equivalent to one shuttle flight.

STS equivalent payload: The payload mass equivalent to one shuttle flight.

sunk costs: Nonrecoverable costs which have already been paid.

surge: The increase in flight rate over nominal levels in the recovery period following a launch system standdown. Surging can also occur in response to temporary increases in transportation demand.

then-year dollars: Dollar values uncorrected for inflation.

upper stages: Propulsive devices which transport a satellite from a starting orbit to its final location. For example, the shuttle may provide satellite transportation to low Earth orbit, whereas an upper stage takes the satellite to a final location in geosynchronous orbit.

upweight: Total payload mass carried to orbit on launch vehicles.

wet weight: Fully loaded weight of a satellite or launch vehicle, including propellants and other fluids.

LIST OF ABBREVIATIONS

AFB	Air Force Base
AHP	Analytic Hierarchy Process
AIAA	American Institute of Aeronautics and Astronautics
ALS	Advanced Launch System
ASRM	Advanced Solid Rocket Motor
ASTP	Apollo-Soyuz Test Program
BA	Budget Authority
BSTS	Boost Surveillance and Tracking System
CBO	Congressional Budget Office
CELV	Complementary Expendable Launch Vehicle
DARPA	Defense Advanced Research Projects Agency
DDT&E	Design, Development, Test and Evaluation
DEW	Directed Energy Weapon
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DOT	Department of Transportation
DRB	Defense Resources Board
DSARC	Defense System Acquisition Review Council
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
ELV	Expendable Launch Vehicle
EOP	Executive Office of the President
ET	External Tank
FLTSATCOM	Fleet Satellite Communications System
FSD	Full-Scale Development
FY	Fiscal Year
FYDP	Five-Year Defense Plan
GAS	Get-Away Special
GEO	Geosynchronous Orbit
GLOMR	Global Low-Orbit Message Relay satellite
GLOW	Gross Lift-off Weight
GNP	Gross National Product
GPS	Global Positioning System
HLV	Heavy-lift Vehicle
ICBM	Intercontinental Ballistic Missile
IOC	Initial Operating Capability
IUS	Inertial Upper Stage
KKV	Kinetic Kill Vehicle
KSC	Kennedy Space Center
LCC	Life-Cycle Cost
LEO	Low Earth Orbit
LH	Liquid Hydrogen
LOX	Liquid Oxygen
LRB	Liquid Rocket Booster

MLV	Medium Launch Vehicle
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
NASP	National Aerospace Plane
NCOS	National Commission on Space
OMB	Office of Management and Budget
OME	Orbital Maneuvering Engine
OMS	Orbiter Maneuvering System
OMV	Orbital Maneuvering Vehicle
O&S	Operations and Support
OSD	Office of the Secretary of Defense
OTA	Office of Technology Assessment
OTV	Orbital Transfer Vehicle
OV	Orbiter Vehicle
P/A	Propulsion and Avionics
PAM	Payload Assist Module
POM	Program Objective Memorandum
RCS	Reaction Control System
SBI	Space-based Interceptor
SBL	Space-based Laser
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SON	Statement of Operational Need
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
SSTO	Single-Stage-to-Orbit
SSTS	Space Surveillance and Tracking System
STAS	Space Transportation Architecture Study
STS	Space Transportation System
STV	Space Transfer Vehicle
TOA	Total Obligational Authority
USAF	United States Air Force
USG	United States Government
VAFB	Vandenberg Air Force Base

I. INTRODUCTION

In the aftermath of a string of launch vehicle disasters in 1986, the United States made major changes in its usage of launch vehicles. New expendable launch vehicles (ELVs) have been procured and space shuttle flight rates have been reduced. Payloads have been delayed, cancelled, or shifted to other launch vehicles. The transition to a mixed fleet of shuttles and ELVs, the emergence of a commercial launch industry, and proposals to build a heavy-lift launch vehicle have characterized this turbulent period in U.S. space transportation.

The launch failures and the consequent disruptions to U.S. launch schedules prompted a variety of responses. The loss of the Challenger led to an inquiry by a Presidential commission. The shuttle disaster and the loss of Titan and Delta ELVs resulted in recovery efforts to replace lost vehicles, ration those remaining, and procure additional vehicles to ensure that the United States would not be as vulnerable to future accidents. Prior to these losses the United States had initiated several studies examining the goals and purposes of the U.S. space program. The Congressionally mandated, Presidentially appointed National Commission on Space (NCOS) recommended a long-range goal of human expansion to the Moon and Mars. NASA's own study of future space goals included a range of options such as increased study of the Earth, unmanned exploration of the Solar System, and human outposts on the Moon and Mars. The Department of Defense was similarly engaged in defining future military space missions, both within and without the Strategic Defense Initiative.

Studies of space transportation in recent years have spanned a wide spectrum. At one end, the United States has concentrated on meeting the pressing problems of recovering from specific failures and meeting budget limits. At the other end, there have been visionary studies of where and how the U.S. space program might develop over the next 50 years. Largely missing, however, have been studies combining a comparison of both means and ends. Such a study would bridge the gap between current problems and the longer term goals that depend on U.S. policy choices. For example, if the United States chooses to pursue space goals having requirements for space transportation, what is the best way to meet that transportation demand?[1] Access to space is not an end in itself, but it is a prerequisite to a space program serving national goals and interests.

1.1 FUTURE DIRECTIONS FOR SPACE TRANSPORTATION

The U.S. space effort today is divided into three sectors: a civil space sector, a national security space sector, and a commercial space sector. This division is reflected in current national space policy (as contained in a National Security Decision Directive signed by then President Reagan on January 5, 1988), the FY 1989 Budget submitted by the President, and a 15-point Commercial Space Initiative.[2] The future of U.S. space transportation will be largely decided by how each of these sectors develop. The civil and national security sectors account for the majority of U.S. space traffic (in number of payloads and tonnage).[3] Decisions affecting these two sectors will decide the direction of most, if not all, U.S. government-funded space transportation efforts. Government policies may help or hinder the commercial

[1]This question has been partially addressed by the Office of Technology Assessment. See Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, U.S. Government Printing Office, OTA-ISC-383, Washington, D.C., July 1988.

[2]The White House, "U.S. national space policy directive" and "The President's space policy and commercial space initiative to begin the next century," *Space Policy*, May 1988, pp. 165–171.

[3]Department of Commerce, *Space Commerce: an Industry Assessment*, Washington, D.C., May 1988, pp. 12–13.

sector, but commercial programs are not as tied to governmental decisions as the civil and national security sectors.

There are at least two major alternatives for the national security sector. The decision to deploy space-based strategic defenses would require a major expansion of space transportation capabilities dramatically beyond historical U.S. efforts.[4] Without such deployments, normal DoD space efforts will continue to require significant space launch capabilities, but they will be comparable to past experience.

For the civil sector, there are at least three major alternatives. The United States may attempt to move quickly forward on the long-range goal of expanding "human presence and activity beyond Earth orbit into the solar system."[5] This could result in the establishment of a permanently manned lunar base, expeditions to Mars, and even space settlements of considerable size.[6] Near-term budgetary realities will argue against such ambitious efforts, however. The second alternative would maintain current plans for NASA's "core" program, including an international, permanently manned space station, new in-space transportation systems (the Orbital Maneuvering Vehicle and Space Transfer Vehicle), continuation of the shuttle program, and new starts in space and planetary science. The Congressional Budget Office has estimated that the NASA budget will need to nearly double by the year 2000 (in 1988) to fund the core program.[7] The third alternative would be to constrain the annual NASA budget to current levels ($9–10 billion) and drastically reduce the scope of its activities, especially in manned spaceflight. This would mean cancelling the space station, curtailing shuttle flights, and purchasing additional ELVs for unmanned science missions.

Deploying large-scale strategic defenses will clearly require new heavy-lift launch vehicles. The same vehicles are also likely to be needed for expanded civil space efforts to the Moon and Mars. In contrast, if the United States withdraws from manned spaceflight under budgetary pressures, the need for new vehicles will fade. The commercial ELV sector may grow, however, as NASA buys vehicles for its remaining unmanned payloads. The most likely case (as later analysis and interviews show)—nominal growth in DoD space activity and continuation of the NASA core program—raises the most difficult questions for transportation planning. The justification for developing new vehicles is made difficult by uncertainties in balancing traffic requirements with the cost and technical risks of new programs. Specific examples of these questions are discussed in Sec. 1.3.

Past experience with government developments has shown that an orderly hierarchy of goals and constraints is not the final determinant of whether a program moves forward or not.[8] Instead, complex processes of conflict and cooperation occur among various organizations and policymakers. The questions raised above depend not only on technical and economic factors, but on political judgments as well. If a consensus is to be reached on the future of U.S. space transportation, the Bush Administration will have to provide strong leadership in defining U.S. interests in space.

Reconciling the many inconsistencies between national space policy goals, strategies, programs, and budgets is beyond the scope of this report. Such reconciliation is needed, however, to make informed choices about how to allocate the nation's resources in space. Consensus on national interests and goals in space can provide the standard against which to compare and evaluate alternative space transportation proposals. Without a common policy basis for the evaluation of alternatives, agreements on the future direction of space

[4]Office of Technology Assessment, *SDI: Technology, Survivability, and Software*, U.S. Government Printing Office, OTA-ISC-353, Washington, D.C., May 1988, pp. 148–156.

[5]This overall goal for U.S. space activity is from the latest articulation of national space policy. See The White House, "Presidential Directive on National Space Policy-Fact Sheet," Office of the Press Secretary, Washington, D.C., February 11, 1988.

[6]National Commission on Space, *Pioneering the Space Frontier*, Bantam Books, New York, May 1986.

[7]Congressional Budget Office, *The NASA Program in the 1990s and Beyond*, U.S. Government Printing Office, Washington, D.C., May 1988.

[8]See, for example: Harvey Sapolsky, *The Polaris System Development*, Harvard University Press, Cambridge, MA, 1972, and Mel Horwitch, *Clipped Wings*, M.I.T. Press, Cambridge, MA, 1982.

transportation are not only difficult to achieve but risk being separated from larger national interests. If U.S. space activity is separated from those interests, the rationale for its support will quickly disappear, along with the U.S. role in space.

1.2 THE SPACE TRANSPORTATION PLANNING PROBLEM

Over the next two decades, the United States will need to provide access to space under severe resource constraints. Decisions are needed not only on the goals of U.S. space efforts, but on how to best meet derived requirements for space transportation. This report evaluates launch vehicle combinations capable of meeting a range of U.S. space traffic needs between 1990 and 2010. The purpose of the evaluation is to clarify alternatives available to the United States in pursuing potential national goals and to increase understanding of the implications of those alternatives.

This study examines U.S. government needs; projections of commercial space transportation demand have not been included. New launch systems are assumed to be government developed, but are not necessarily government owned and operated. Space transportation is here limited in definition to transporting cargo to orbit, and not in-orbit operations or manned spaceflight per se (although manned systems may certainly carry cargo). Finally, all transportation demands are assumed for peacetime operations and not deployments or launch surges during wartime, which may have very different requirements.

Within these constraints, the study attempts to answer two questions. The first is: *Which launch vehicle options are best for the United States?* The definition of "best" is open to debate as it likely means the combination of a diverse range of criteria. Different institutions responsible for space transportation planning can be expected to have different views of what is "best" for themselves and the United States as a whole.

The second question is: *What and when are the decision points for choosing the best option?* This also will depend on who is answering the question. Different decision points can be expected depending on specific assumptions made as to future levels of space traffic, national policy directives, changing technical conditions, and so forth. Again, responsible institutions might be expected to have different viewpoints based on their assumptions about the future.

No recommendations are made as to which goals the United States should pursue in space. Rather, recommendations on launch vehicle choices are made for cases where future space traffic is given (i.e., a policy choice has been made) and for where it is uncertain (i.e., where policy choices are deferred). The study is thus an evaluation of the preferable means of space transportation for a range of purposes.

1.3 THE ASSESSMENT PROCESS

To recommend what launch vehicle mix the United States should choose, an assessment is required to determine what the United States can and is likely to do in space transport for the next two decades. This assessment in turn will depend on the range of space traffic demands and possible launch vehicle alternatives.

Government-sponsored studies, such as the Space Transportation Architecture Study (STAS) and the Advanced Launch System (ALS) program, were reviewed in developing a spectrum of space transportation demands. (See Sec. 3.2.) A set of four traffic demand projections was then defined to represent distinct levels of U.S. effort in space. (See Sec. 3.3.) The lowest level was termed a constrained demand, corresponding to a major slowdown in space activity due to budgetary constraints. The highest level was termed an expanded DoD demand, corresponding to a full deployment of space-based strategic defenses.

There are several launch vehicle options available to the United States in the coming two decades. (See Sec. 4.2.) The shuttle and ELVs such as the Titan, Atlas, and Delta lines

make up the current U.S. launch vehicle mix. This may continue into the future, possibly with evolutionary improvements in each. The United States may decide to build a Shuttle-C, which would be an unmanned heavy-lift vehicle based on shuttle components. Another option would be to build a new family of unmanned launch vehicles with greatly reduced operating costs and greater reliability and availability. These are the goals of the Advanced Launch System program. A more technically difficult possibility is that the National Aerospace Plane (NASP) program may open the option of a single-stage-to-orbit vehicle capable of launching and landing on conventional runways. An operational vehicle from this program was not considered as its associated risk placed the probable initial operating capability (IOC) date beyond the 1990–2010 time frame.

Budgetary constraints, in both the civil and national security sectors, and the many alternatives listed above lead to more specific formulations of the two questions posed in Sec. 1.2. For example:

- Should the United States purchase more ELVs to support civil and national security space goals?
- Should the United States build a Shuttle-C? How does this relate to the ALS and space station efforts?
- Should the United States continue the ALS program without either a commitment to deploying strategic defenses or ex-panding civil space efforts?
- How should the United States plan for manned access to space beyond the space shuttle?

These questions highlight particular issues that the assessment process will answer. (See Sec. 4.3.)

There are many complex issues of cost, risk, performance, and programmatic tradeoffs associated with alternative U.S. launch vehicle mixes. Cost estimates are made for launch vehicle mixes capable of meeting each of the four traffic demand projections. (See Sec. 4.4.) Separate estimates are then made of the risks due to launch vehicle reliability and standdown delays posed by each alternative mix. (See Sec. 4.5.) Finally, estimates are made of the degree of budgetary growth required to support each applicable combination of launch vehicles and payloads for the four demand projections. (See Sec. 4.4.).

Analysis is necessary to understand the implications of various combinations of launch vehicles and traffic demands, but it is not sufficient to implement a plan for space transportation. The relative importance of launch vehicle mix implications must be assessed by the decisionmakers responsible for such planning. Technical factors such as vehicle reliabilities, payload capacities, and associated costs must be evaluated in the context of budgetary constraints, policy directives, and organizational conflicts. (See Sec. 5.1.)

Space transportation decisionmakers are distributed across several institutions, such as the Department of Defense, NASA, the Congress, and the Administration. Interviews were conducted with several decisionmakers to identify the important criteria used to evaluate space transportation plans by their institutions. (See Secs. 5.2 and 5.3.) These criteria provided the means for weighing the independent analyses of alternative launch vehicle mixes mentioned above. (See Sec. 6.2.) The combination of analyses and institutional criteria led to recommendations of which launch vehicle mixes should be preferred for the 1990-2010 period. (See Sec. 7.1.)

A further purpose of the interview process was to identify areas of consensus and disagreement among space transportation decisionmakers to help define a common basis for institutional negotiations in implementing launch vehicle decisions and measures for reducing related planning uncertainties. (See Sec. 5.4.)

1.4 A PREVIEW OF THE CONCLUSIONS AND RECOMMENDATIONS

The United States faces many uncertainties and difficult choices in space transportation and space policy as it moves toward the end of the century. New technology efforts should be supported while incremental improvements are made in the capabilities of the shuttle and ELV fleets. Currently funded technology programs could continue during periods of budgetary stringency, yet provide options for expansion as economic and technical opportunities became available. Commitments to full-scale development of new vehicles should await the arrival of those opportunities.

A mixed fleet of existing ELVs and the shuttle can and should provide the backbone of U.S. access to space in the next decade. *Decisions to develop an operational NASP and ALS heavy-lift vehicle should be deferred until their technical benefits become more compelling or until national needs (such as increased traffic demands) emerge for their adoption.*

The Shuttle-C's cost makes it undesirable for carrying normal space traffic. However, it may be desirable in reducing the number of shuttle flights, assembly times, and associated risks of the space station's deployment and initial operation. The net costs and benefits of this vehicle to the space station effort were not addressed in this report, which looks at broader national demands for space transportation. *An independent assessment of the Shuttle-C program should be conducted soon and a recommendation made to the Bush Administration on whether to proceed to full-scale development, depending on the schedule of the space station program.* Failure to fully evaluate the Shuttle-C for the space station program may result in unnecessary costs and risks to the station effort.

In Sec. II, the recent history of space transportation planning is reviewed, leading up to current issues and key questions. This history and the associated players constitute the background environment for evaluating U.S. space transportation options.

II. THE POLICY CONTEXT FOR SPACE TRANSPORTATION PLANNING

2.1 INTRODUCTION

Prior to the loss of STS (Space Transportation System) flight 51-L on January 28, 1986, NASA had been phasing out the use of expendable launch vehicles. The Department of Defense was reluctant to depend solely on the shuttle for its payloads, although national policy statements had consistently cited the shuttle as the nation's "primary" means for access to space. After an extended debate in the early 1980s, the Department of Defense received permission to procure ten "complementary" expendable launch vehicles (CELVs)[1] as a backup to the shuttle to ensure that critical national security payloads could be launched even if the shuttle were unavailable.

In the aftermath of the loss of the Challenger, the makeup of the U.S. space transportation fleet has undergone a dramatic change. The DoD effort to continue the procurement of its own launch vehicles seems to have shown great prescience; even NASA is buying ELVs to make up for the drop in future shuttle flight opportunities. The Department of Defense has expanded its Titan 4 purchases and has initiated two more near-term procurements of medium launch vehicles (MLVs) as well as a program to develop a new heavy booster, the Advanced Launch System.

The Bush Administration faces a series of complex issues on the future role of the United States in space, as well as tough decisions on how to pay for it all. Reliable, cost-effective space transportation is widely cited as being critical to the pursuit of the U.S. military, commercial, scientific, and foreign policy interests in space. Given the importance, cost, and technical nature of these interests, it would seem that space transportation would be an obvious candidate for planning and analysis efforts. As part of the context for later analyses and interviews on launch vehicle choices, this section addresses two questions:

- What is the current state of space transportation plans and how has it come about?
- Who are the major players in the space transportation planning process?

2.2 HISTORICAL BACKGROUND

2.2.1 The Space Shuttle

While the Apollo program neared its first lunar landing in 1969, NASA planners were drafting a blueprint for continuing ambitious efforts in space. A Space Task Group, chaired by the Vice President, presented a range of options, from a manned mission to Mars, to a lunar base, to a combination shuttle/space station complex. The upper options were "technology-constrained," whereas the lower ones were identified as "minimal budget" levels.[2] NASA did not yet suspect that its budget would fall below what it considered "minimal."

[1] Now termed the Titan 4.

[2] A more complete discussion of the decision to build the space shuttle can be found in John M. Logsdon, "The decision to develop the Space Shuttle," *Space Policy,* May 1986, p. 103–119; and Scott Pace, *Engineering Design and Political Choice: The Space Shuttle 1969–1972,* Master's thesis, M.I.T., Cambridge, MA, 1982.

In the 1969–1970 period, the space station was NASA's central goal—a facility it thought crucial to any other manned space efforts such as a lunar base or manned mission to Mars. The space shuttle was merely a reusable (thus hopefully cheaper) means of supporting the station. NASA and the Department of Defense, via the Air Force, formed a joint Space Transportation Committee to coordinate the interests of both agencies. Earlier working groups had endorsed the possibility of one vehicle being usable by both civil and military payloads, but this did not entail a commitment by either side to this concept.

As the degree of post-Apollo cutbacks became clear, NASA abandoned its plans for a Mars mission, lunar base, and even the space station. In addition to the upcoming Skylab missions and some unmanned planetary probes, NASA chose building the shuttle as the program that would sustain it in the dry years it saw ahead. In the course of defending the shuttle in an austere environment, the terms of the space policy debate were changed from one of "beating the Russians" to "cost-effectiveness." Under pressure from the Office of Management and Budget, NASA commissioned a series of studies to economically justify a shuttle system.[3]

The economic studies had two major effects on the shuttle program as a whole. The first was a narrowing of the debate over shuttle to cost-effective space transportation options, as opposed to more general discussions of what the United States should be doing in space. The second was a more subtle impact on the projected payloads for the shuttle. While the per-flight cost of a shuttle would be (it was hoped) cheaper than current expendable launchers, many flights would be needed to amortize the shuttle's development costs. The "mission model" for the shuttle was expanded to show how flying the shuttle many times (e.g., five vehicles, flying once a month, for 60 flights a year) would result in a cost-effective vehicle. This begged the question, of course, on whether such payloads and budgets for their development would be available. An added consequence of raising the projected flight rate was the need to include DoD payloads in the projections. Thus the needs of economic justification and building coalition support for the shuttle reinforced each other.

2.2.2 Transition to the Shuttle Era

With the first flight of the space shuttle in 1981, NASA looked forward to transitioning all space transportation needs to the shuttle, raising its flight rate, and phasing out its purchases of ELVs. In a statement of National Space Policy in 1982, the space shuttle was cited as "a major factor in the future evolution of United States space programs" and as the "primary space launch system for both United States national security and civil government missions."[4]

The Air Force was not comfortable with relying only on the shuttle, but its ELVs were already being phased out. In early 1983, Secretary of the Air Force Edward C. Aldridge sent a memorandum to Secretary of Defense Caspar Weinberger advising him of the Air Force's intent to suspend further procurements of Titan ELVs.[5] The Titan family had been the mainstay of DoD launch capability, and Secretary Aldridge attempted to hedge his bets by encouraging efforts by Titan contractors to produce versions of the Titan for the commercial satellite market.[6]

[3]Mathematica, Inc., *Factors for a Decision on a New Reusable Space Transportation System*, report to James Fletcher, NASA Administrator, October 28, 1971; Mathematica, *Economic Analysis of the Space Shuttle System*, NASA-CR-129570, Princeton, NJ, January 31, 1972; and Mathematica, *Economic Analysis of New Space Transportation Systems*, NASW-2081, Princeton, NJ, May 31, 1971.

[4]Office of the White House Press Secretary, press release on National Space Policy, Washington, D.C., July 4, 1982; based on National Security Decision Directive 42.

[5]E. C. Aldridge, (Acting) Secretary of the Air Force, "Titan Procurement-Action Memorandum," Memorandum for the Secretary of Defense, March 31, 1983.

[6]T. M. Jenkins and R. M. Davis, "Commercial Titan ELV, Filling a Need in the National Space Transportation System," *AIAA/SAE/ASME 19th Joint Propulsion Conference Proceedings*, AIAA-83-1193, Seattle, WA, June 27–29, 1983.

As shuttle flight rates continued to increase in 1984 and 1985, the Air Force decided to pursue vigorous efforts to keep open the Titan production lines. In early 1985, it was successful in being allowed to buy ten "complementary" ELVs or CELVs for the 1988–92 period.[7] After some competition from a design based on shuttle solid rocket boosters (the SRB-X), the Titan 34D7 vehicle was selected as the CELV, and soon became known as the Titan 4.

In the same National Security Decision Directive (NSDD) which allowed for CELV procurement, NASA and the Department of Defense were directed to "jointly study the development of a second-generation space transportation system, using both manned and unmanned systems, to meet the requirements of all users."[8] This was not quite the repeat of studies from the early 1970s, but rather an attempt at defining a range of space transportation "architectures" that would integrate several different vehicle systems. In October 1985, contracts were awarded to Rockwell International, General Dynamics, Boeing, and Martin-Marietta in support of this Space Transportation Architecture Study (STAS).

One of the major results of the STAS efforts was a definition of common civil and military mission models for planning efforts. These models spanned a wide range of options from constrained (no new program starts) to very ambitious (full deployment of Strategic Defense Initiative systems and manned Mars missions). These models were based on inputs from throughout the government, as well as from NASA and the Department of Defense. As such, they represented lists of desirable options, as opposed to validated mission requirements with associated budgets.

2.2.3 The Shuttle Accident and Its Impacts

Four months before the STAS study contractors were to deliver their mid-term reports, the space shuttle Challenger was destroyed. In addition to losing a quarter of the shuttle fleet, the accident led to a standdown of over two and one-half years and contributed to the cancellation of the shuttle-based Centaur upper stage. This was a liquid hydrogen/oxygen upper stage that, starting from a shuttle deployment in low Earth orbit, could place payloads of about 10,000 lb in geosynchronous orbit.[9] The next largest shuttle upper stage was the IUS (inertial upper stage), which could only place about 5000 lb in geosynchronous orbit.

After the accident, the United States decided to build a replacement shuttle orbiter and to limit the use of the STS to shuttle-unique payloads. This meant that if a payload, especially a commercial one, could go on an ELV, it would be ineligible for a shuttle flight. This had the effect of greatly bolstering the U.S. ELV commercialization effort and signaled the final abandonment of attempts to justify the shuttle on cost-effectiveness grounds.

The events of 1986 led to renewed Air Force efforts to procure its own fleet of ELVs.[10] The cost of the DoD space recovery effort has been placed at almost $12 billion, and the Air Force has initiated or expanded four booster programs.[11] The original buy of ten Titan CELVs has been expanded to a total buy of 23 Titan 4s, the only booster capable of putting heavy payloads into geosynchronous orbit. A medium launch vehicle program was initiated to put up the Navstar navigation satellites removed from the shuttle manifest. This resulted in a buy of 20 Delta II launch vehicles. Another medium launch vehicle program (MLV 2) procurement will buy 11 Atlas-Centaur 2 vehicles to launch defense communications

[7]The White House, *National Security Launch Strategy*, NSDD 144, February 28, 1985.

[8]Ibid.

[9]The shuttle Centaur upper stage was based on a previously developed upper stage used with the Atlas ELV family. It was cancelled because of safety concerns over placing a liquid propellant system in the shuttle's payload bay.

[10]Prior to the Titan 34D loss in 1986, a Titan 34D was lost on August 28, 1985. On March 26, 1987, an Atlas-Centaur was lost on liftoff due to a lightning strike.

[11]"Military Launcher Programs Meeting Critical Milestones," *Aviation Week and Space Technology*, February 1, 1988, p. 36.

satellites to geosynchronous orbit. Fourteen decommissioned Titan 2 vehicles are available for polar orbit missions, such as those launching DoD weather satellites. An additional 41 Titan 2s are available for conversion.

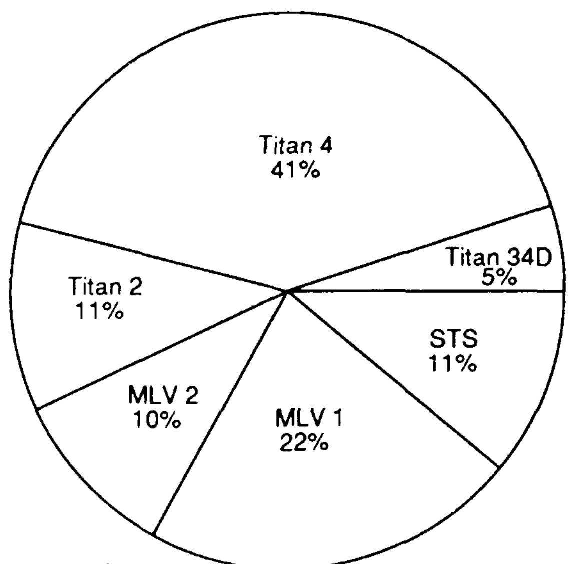
The Department of Defense is distributing its payloads over six different launch vehicles, some of them virtually dedicated to particular programs. The MLV 1 and 2 procurements followed the Challenger disaster, whereas the Titan procurements were under way prior to that event. Figure 2.1 shows the planned distribution of DoD launch vehicles in the 1991–95 time frame.

NASA has also moved to acquire ELVs, but not to the same degree as the Department of Defense. As Fig. 2.2 shows, NASA is still planning to use the shuttle for the majority of its flights between 1991 and 1995. The Delta launch vehicle is planned for use with a number of small scientific and communications payloads that were removed from the shuttle following the Challenger failure.

The government response to the 1986 launch vehicle failures and the problem of providing "assured access to space" has consisted of three approaches: ration existing capacity (as in the removal of most commercial satellites from the shuttle), rebuild capacity by buying more existing expendable launchers and a replacement orbiter, and begin development of new launchers to expand the supply of space lift. *It is the creation of new capacity that leads to many of the current questions on space transportation planning.*

2.3 CURRENT QUESTIONS IN SPACE TRANSPORTATION PLANNING

It is not surprising that space transportation planning has become linked to continuing debates over the size of the U.S. government budget. The expense of current launchers and their long lead times make them similar to other major procurements such as military vehicles for airlift and sealift (which carry out functions analogous to DoD ELVs).



94 Launches

SOURCE: *Aviation Week and Space Technology.*

Fig. 2.1—DoD launch vehicles, 1991–1995

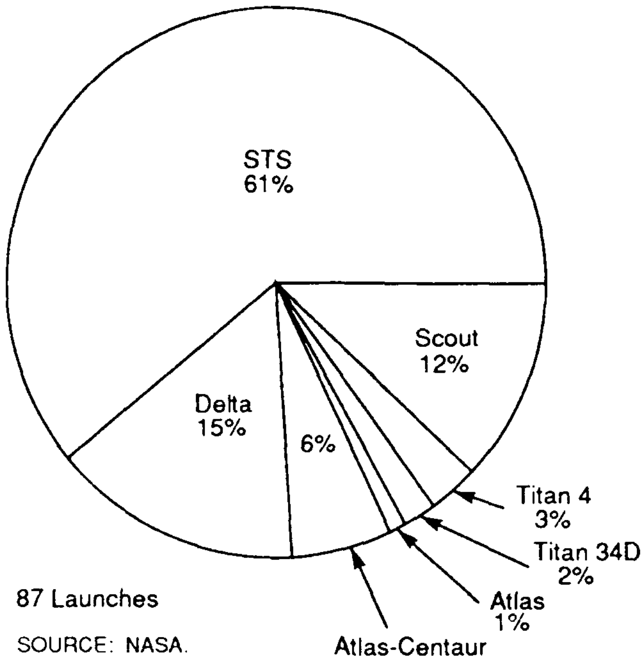


Fig. 2.2—NASA launch vehicles, 1991–1995

Late in 1987, the Senate Appropriations Committee complained that the combined space plans of NASA and the Department of Defense would total more than $46 billion through the mid-1990s. These costs were cited as:[12]

- $11.7 billion for the Air Force's Space Recovery Program
- $18.9 billion for the Advanced Launch System
- $1.5 billion for a NASA shuttle-derived heavy booster
- $14.6 billion for the NASA space station

plus "additional billions" for what were described as "other military space activities." The committee stipulated that some $316 million for funding the Space Recovery Program would not be committed until the President submitted "an overall Space Recovery Program reconciling the separate Department of Defense and NASA programs to meet the nation's present and future (FY 2000) space launch requirements."

The plan desired by the Senate committee would ideally provide a comprehensive explanation of how all the separate unmanned and manned launch vehicles, payloads, and facilities proposed by the Department of Defense and NASA fit together, the annual costs for the plan, and a development and acquisition strategy. This kind of information is what one might have expected to have emerged from the Space Transportation Architecture Studies, even after they had been interrupted by the Challenger accident.

The STAS studies had recommended the creation of a heavy-lift cargo vehicle (100,000 lb or more to low Earth orbit), followed by a heavier, partially reusable, cargo carrier (150,000 lb to low orbit), a two-stage fully reusable Shuttle II arriving around 2005, and an unmanned cargo return vehicle.[13] These recommendations did not (nor were they intended to) help the

[12]"DoD, NASA Space Plans Questioned by Senate Appropriations," *Aerospace Daily*, December 10, 1987, p. 369.

[13]"STAS Architecture Team Recommendation to the Joint Steering Group, 5/12/87," from a briefing on *Planning NASA's Space Transportation Program* by Arnold Aldrich, Director of the National Space Transportation System, NASA Headquarters, March 1, 1988.

near-term planning problems such as the number of existing ELVs to buy, whether to build a replacement orbiter, or how payload capacity remaining after the shuttle accident should be allocated. The STAS studies focused on longer range—1995–2010—questions, which were themselves dependent on what future scenario of future space activity one chose to believe.

Within a wide variation of potential space traffic requirements, the United States faces the difficult task of deciding how to best allocate its limited budgetary resources. Current costs for the shuttle and ELVs are already cause for concern, not to mention projected costs for new heavy-lift vehicles. Aside from tight budgets, uncertain requirements, and technical uncertainties, space transportation planning analysis is complicated by a variety of institutional and political issues. The impact of these issues on the conduct of space transportation planning is examined next for the case of the Advanced Launch System program.

2.4 THE DEVELOPMENT OF AN ADVANCED LAUNCH SYSTEM

The ELVs now being bought by the Department of Defense are largely derivatives of ICBM technologies from the 1950s and 1960s. While thought to be satisfactory for current needs, the Department of Defense has expressed the desire for improvements in areas such as:[14]

- Increased cap[illegible]
- Lower costs
- Increase[illegible]ability
- Resilience to accidents and other threats
- Greater flexibility in satellite assignment to vehicles
- Faster responsiveness to launch on demand

To make these improvements in space transportation beyond the current recovery period (through 1995), the Department of Defense in 1987 initiated an Advanced Launch System (ALS) development effort in cooperation with NASA. Seven contracts were let to a variety of aerospace firms for concept definition studies on unmanned heavy-lift launch vehicles. Initially, there were to have been two vehicles: an "interim" vehicle available by about 1993, and an "objective" vehicle by 1998. The difference between the two was that the first would fly payloads at about $1500 per pound, whereas the second would fly at about $300 per pound.[15]

At the same time NASA was getting involved with the ALS program, it was examining the use of shuttle components to build an unmanned heavy-lift vehicle. This Shuttle-C (C for cargo) was to be launched from existing facilities at Cape Kennedy. Its main rationale was to support the deployment and operation of the space station and to relieve the shuttle of some flights. In its study of the space station, the National Research Council (NRC) recommended the creation of a heavy-lift vehicle, but did not directly endorse the Shuttle-C. With respect to using the ALS for the space station, the Committee concluded that it did not "believe that an interim vehicle can be depended on from the Advanced Launch System Program on schedules roughly consistent with the Block I Space Station deployment."[16]

Both NASA and DoD planners thought it unlikely that both a Shuttle-C and an interim ALS would be funded. The interim vehicle option was eliminated, but not directly because of competition from the NASA concept. Congressional staff were concerned that an interim

[14]Statement of Secretary of the Air Force E. C. Aldridge to the U.S. Senate, March 25, 1988.

[15]Shuttle and Titan 34D costs were estimated to be about $3000 per pound then, thus $1500 was one-half of that, and $300 was an order of magnitude reduction.

[16]National Research Council, Report of the Committee on the Space Station, National Academy Press, September 1987, p. 23.

ALS could be used to support near-term SDI deployment,[17] and thus language was inserted into the final conference report authorizing DoD expenditures for FY 1988 and 1989 stating:

> Any request for proposals issued by the Department of Defense for the ALS program 1) shall include as a goal a cost per pound of payload placed in low earth orbit of $300 or less (in constant FY 1987 dollars); and 2) may not include a request for bids or proposals for an interim capability that would have a higher cost per pound of payloads than specified under paragraph (1).[18]

This requirement did not ensure that the Shuttle-C would be developed, but did remove the ALS as a near-term competitor. The chances of the Shuttle-C being funded now appeared remote due to its high cost per flight and its limited period of utility (e.g., for the space station prior to the advent of a heavy-lift ALS).

The Air Force has taken pains to protect the ALS from being seen solely as an SDI-supportive effort. Rather, the ALS is now cited as "the future of our national space launch capability."[19] Aside from SDI deployments, ALS is planned as a technology program for the "next-generation" of launch vehicles in the late 1990 to early 2000 time frame. Current first launch for the ALS vehicle has been suggested for 1996, with an actual IOC in 1998.[20]

The ALS is now defined as not just one heavy-lift vehicle, but a "family" of vehicles that can handle the entire range of potential payloads while lowering the cost of space transportation. In light of the Shuttle accident and subsequent disruptions in launch schedules, it is not surprising that vehicle reliability and resilience to accidents are also listed as primary ALS program goals. Finally, it is hoped that ALS-developed technologies can be spun-off to increase the reliability and lower the cost of existing ELVs.

2.5 THE PLAYERS IN SPACE TRANSPORTATION PLANNING: THE ALS CASE

The future of the ALS will be determined by four players, the Congress, the Administration, the Department of Defense, and NASA. These four groups, with internal variations, also determine the direction of U.S. space transportation as a whole. As long as space traffic consists of predominantly government-developed payloads flying on government-developed boosters, space transportation will be directed by agreements among these four groups.

2.5.1 Congress

Each of the major committees in the House and Senate—Budget, Authorizations, and Appropriations—will want to have some say in the ALS program. Predominant among their concerns will be whether the ALS is actually needed and if so, whether funds are available to support it. NASA is heavily committed to the space shuttle and space station programs and it supports only those efforts which "satisfy unique civil requirements not addressed by the joint ALS baseline design."[21] In contrast, the Department of Defense has accepted funding responsibilities for the program as it believes requirements exist for the improvements promised by the ALS.

[17] Interview with Richard Dal Bello, Office of Technology Assessment (OTA), February 2, 1988.

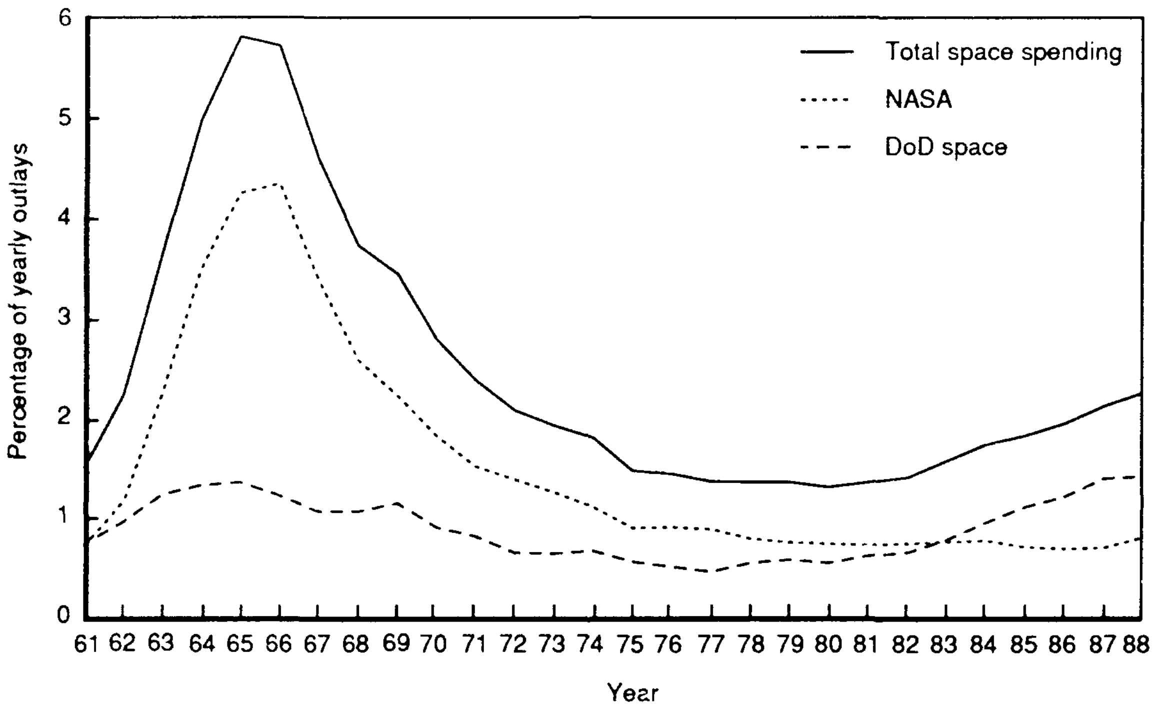
[18] "National Defense and Authorization Act for Fiscal Years 1988 and 1989, H.R. 1748, Section 256," *Congressional Record-House*, November 17, 1987, H10134.

[19] Aldridge, March 25, 1988, op. cit.

[20] U.S. Air Force Systems Command and NASA, *ALS Phase II-Preproposal Briefing*, briefing at USAF Space Division, El Segundo, CA, April 27, 1988.

[21] James Fletcher, NASA Administrator, and Frank Carlucci, Secretary of Defense, *Advanced Launch System (ALS) Report to Congress*, The White House, Washington, D.C., January 4, 1988.

Military space activities are a fast growing segment of the DoD budget; as budget deficit pressures slow DoD growth, space activities have come under increasing scrutiny. Figure 2.3 shows how outlays for space activity have been increasing in recent years, driven by the Department of Defense. Congressional committees with DoD oversight roles are concerned with how much funding the ALS will require. ALS expenditures affect not only the DoD budget, but more specifically the Air Force. Within the Air Force, expenses for space activity must be traded off against activities such as procuring fighters, bombers, and transports.



SOURCE: Office of Management and Budget.

Fig. 2.3—Space as a percent of U.S. government outlays

It is not just the total amount of ALS funding that matters, but the peak year funding requirement as well. It is the peak year requirement that determines the point of maximum "fiscal pain" in squeezing other programs that year. Budgets for the ALS, like those for other major systems, will have to confront tradeoffs between recurring and nonrecurring costs. High recurring costs may make a system unsustainable in routine operations as it costs too much each year to run. Some ALS program options may offer savings on recurring costs, but at the expense of higher up-front (or nonrecurring) costs. This choice then exacerbates the peak funding problem and pushes budgetary choices closer to current political events. Even if peak funding requirements are tolerable, the rate of funding growth can raise "equity" issues in comparison to other programs. For example, a 20 percent growth in the ALS budget may be justifiable on technical grounds, but politically difficult if other desirable programs receive "only" 5 percent.

In addition to asking whether the ALS is needed at all, the Congress will ask about why a new vehicle, family of vehicles, or new technologies should be produced, rather than continue to use current production ELVs. Monies for the ALS may detract, for example, from

increased procurements of Titan 4s or creation of an upgraded Titan 5. This is more than a technical question, in that Congressional districts in which ELVs are produced will have incentives to keep those production lines going.

"Pork barrel" politics has already affected the ALS program. Senator John Stennis (D-Miss.), the chairman of the Senate Appropriations Committee, made it clear that he would like to see the NASA National Space Technology Laboratory (NSTL) facilities in his home state utilized.[22] To ensure the support of this key senator, a statement was included in the NASA-DoD ALS Report to Congress that "the ALS program will make maximum use of Federal testing facilities. . . . As an example, the existing rocket propulsion facilities which will be used for ALS testing are located at the National Space Technology Laboratories (NSTL). . . ."[23]

2.5.2 Administration

The most senior space policy player within the Administration has been the National Security Council Senior Interagency Group for Space (SIG-Space). This group carries out the interagency review of national space policy through officials designated from the major institutions concerned (chiefly the Department of Defense and NASA). Its primary concern is ensuring a coherent integration of the often differing viewpoints of agencies with an interest in space transportation. It serves as a forum for the arbitration of disputes that rise to (or which are taken up by) the White House.

The NASA authorization bill for FY 1990 contained language creating a National Space Council chaired by the Vice President. Other members are the secretaries of State, Defense, Commerce, and Transportation, directors of the Office of Management and Budget and the Central Intelligence Agency, the President's chief of staff, assistant to the President for national security affairs, and the NASA administrator. The chairman of the Joint Chiefs of Staff, the President's science and technology advisor, and other senior executive branch officials are to participate as appropriate.[24] It is not yet clear, however, what role this council will play in the interagency process. One possibility is that it will serve as forum for the most senior officials when the usual interagency process becomes deadlocked.

Like the Congress, the Administration is concerned with the budgetary impacts of ALS choices. Also like the Congress, these choices are not limited to the overall size of the budget, but influence different portions of the country. The next most important player within the Administration is the Office of Management and Budget (OMB). The OMB's importance to the policy process had been growing under President Carter, but began to increase even more rapidly under President Reagan, especially under his first budget director, David Stockman. As the shaper of the fiscal options affecting the ALS, the OMB is in a key position to make the tradeoffs between pursuing this program or some other activity.

A final player, although a minor one in this case, is the Office of Commercial Space Transportation in the Department of Transportation. It is concerned with regulating and encouraging the commercial U.S. ELV industry. This affects the ALS in terms of support for existing production lines of ELVs, as well as providing potential alternatives to the ALS itself. Commercial interests in space have been represented in the past through the Interagency Space Commercialization Working Group under the Economic Policy Council (which is chaired by the Secretary of the Treasury). The National Space Council will likely have responsibility for this interagency process in the future.

In adjudicating the different priorities of NASA and the Department of Defense, the Administration must struggle with basic issues of the balance between civil and military

[22]These facilities were also used for developing and testing shuttle main engines. They were recently renamed in honor of Senator Stennis, who retired from Congress in 1988.

[23]Fletcher and Carlucci, op. cit.

[24]"Bush scopes goals of space council," *Space Business News*, March 6, 1989, p. 5.

space efforts. An example of this question concerns whether the Air Force or NASA will be the predominant developer of the next major space transportation system. NASA developed the space shuttle, whereas the Air Force developed the Titan launch vehicle family. While NASA is concentrating on a space station, the Air Force is the primary source of funding for the National Aerospace Plane (NASP) program, another potential space launch vehicle. Between NASP and the ALS, the Air Force, not NASA, appears to be the leading developer of new space launch systems. There are many reasons for this situation, but as the Administration sets its budget priorities, it might ask whether a more balanced space effort requires a larger civil sector role in developing new launchers.[25]

2.5.3 Department of Defense

The Department of Defense, and the Air Force in particular, is the most complex player in space transportation policy. This stems from the many different organizations affected by the ALS and their differing views of it. These views in turn depend on what each organization sees as the future of military space operations and their perceived roles in that future. If the decision were made to deploy an SDI system, then there seems to be no question that existing launch vehicles are inadequate and an ALS would be required.

Aside from a potential SDI deployment, the military requirements for an ALS are less clear. Current military satellite programs do not wish to depend on the development of a new generation launch vehicle. They need vehicles now, and hence the procurement programs for MLVs 1 and 2, Titan 4s, and Titan 2s. This leaves the awkward question of what payloads the ALS would launch, if current ones are already assigned and an SDI deployment does not occur. Some transition plan would have to be developed to move upcoming satellites onto the ALS and off existing launchers. The question then becomes one of identifying likely military (and civil) payloads for the ALS. Large, single vehicles might appear to be efficient launchers, but they can suffer limited flexibility when launching multiple satellites. The vehicle may be able to lift multiple satellites, but the satellites may require different orbits that have incompatible launch windows.

There are many motives for an ALS, but the primary one seems to be the desire to drastically cut launch costs, an obvious benefit in a tight fiscal environment. One benefit is that the space sectors of the Air Force (e.g., Space Command, and Space Division within the Air Force Systems Command) will have an easier time in competing for funds with more traditional Air Force organizations (e.g., the Strategic Air Command), since their future programs will be less costly.

More so than the Administration and Congress, the Department of Defense is concerned with the technical aspects of the ALS. This is not just a concern with engineering design, but with how well the ALS will meet the needs of the Department of Defense. Some examples of the questions being asked by the Department of Defense and the Air Force are:

- What cost per pound to low Earth orbit can actually be expected?
- What is the optimum payload size?
- How can this size be varied to capture the widest range of payloads?
- To what reliability level can and should the ALS be designed?
- How resilient is the ALS to accidents or disruptions of its industrial infrastructure?
- How quickly can backlogged payloads be launched if the ALS has to standdown?
- What ALS technologies should be given priority?
- What ALS-related technology developments can be usefully applied to current ELVs, or even to the space shuttle?

[25]The Defense Advanced Research Projects Agency (DARPA) is also funding efforts aimed at creating a small satellite launch vehicle. See, for example, Craig Covault, "Relay Satellite, Gas Release Payload Scheduled for Pegasus Winged Booster," *Aviation Week and Space Technology*, January 9, 1989, p. 59.

These questions should be answered after ALS design studies are completed by the Air Force and its contractors. The next problem will be to determine whether to continue with ALS, redirect it, or depend on incremental upgrades of current ELVs as needs arise.

2.5.4 NASA

The Department of Defense is responsible for funding the ALS, but NASA centers and personnel are planned to support the program. NASA has the lead in two key aspects of the ALS, the development of ALS-focused technology and liquid rocket engines. Whereas technology efforts may involve almost any NASA center, the development of liquid rocket engines will be assigned to the Marshall Spaceflight Center in Huntsville, Alabama. Within NASA, that center has been designated as having responsibility for such work since the days of Wernher Von Braun and the Apollo program.

NASA's Office of Space Flight has been interested in developing an unmanned shuttle-derived cargo vehicle for many years. Spurred on by the recommendations of the National Research Council's report on a space station, NASA and the Marshall Space Flight Center have been trying to win approval from the Congress for a Shuttle-C.[26] When the ALS program included an interim launch vehicle, it was clear that both vehicles would not be funded by Congress. With the deletion of an interim ALS, there was no longer a direct conflict between NASA and Air Force plans. Instead, budgetary tensions within NASA have sharpened.

Cost estimates for the space station have climbed and the NASA Office of the Space Station is reluctant to do anything, such as support the Shuttle-C, that would raise cost estimates further. The Office proposes to use advanced solid rocket motors (ASRMs) with the Shuttle and to deploy and support the station solely with this upgraded system. While this is feasible, Shuttle-C proponents argue that their larger vehicle would require fewer flights to deploy the station, would allow assembled components to be sent up (saving on on-orbit assembly time), and would be safer than requiring a manned shuttle for simple cargo flights.

NASA's concerns with the ALS are not immediately budgetary, but focus on how ALS development will affect NASA's influence on space transportation policy. The Challenger accident resulted in the bulk of DoD shuttle payloads being shifted to ELVs and the removal of ELV-compatible commercial payloads. In some ways, this was fortunate in freeing remaining launch capacity for the station effort. But it also means the shuttle will fly fewer times, the "standing army" of support must spread its costs over a narrower base, and thus per flight shuttle costs (if not prices) will increase.

If the Department of Defense is to meet its cost per pound goals, it will have to launch many payloads to spread its fixed costs. One source of those payloads outside of the DoD budget is NASA. This could create problems for NASA around the year 2000 as it tries to win approval for a follow-on to the aging shuttle fleet such as building a Shuttle II or developing a NASA version of the National Aerospace Plane.[27] The Department of Defense and NASA could be competing for the same "pool" of government-developed payloads (whose number is also restricted by budgetary concerns). If the Department of Defense is successful in developing a truly low-cost launcher, this would be beneficial for the United States but a potential threat to NASA's role in space transportation development.

In the next section, a range of space traffic demand levels is discussed and baseline projections are defined. In Sec. IV, these baseline demand projections are used to assess

[26]National Research Council, op. cit.

[27]Scott Pace, "The Aerospace Plane: Goals and Realities," *Issues in Science and Technology*, Spring 1987, pp. 20–24.

alternative mixes of U.S. launch vehicles. The assessments cover the ability of each mix to meet the traffic demand, the cost of the mix, and its expected risk. Section V treats the institutional perspectives involved in evaluating and selecting a launch vehicle mix.

III. ALTERNATIVE LEVELS OF U.S. SPACE TRAFFIC DEMAND

3.1 APPROACH

The purpose of this section is to define alternative levels of space traffic demand for the assessment of major U.S. launch vehicle options. Each demand level covers the 1990–2010 time period and assumes a notional set of U.S. goals to be met. As the assessment is directed to U.S. government needs, projections of commercial space transportation demand are not included. The definition of alternative demand levels consists of three major steps:

1. Near-term space activity is defined by the 1988 manifests of NASA and DoD launches through 1995. This includes both Shuttle and ELV flights;
2. Two government studies, the Space Transportation Architec-ture Study (STAS) and the Advanced Launch System (ALS), have made a wide range of demand estimates. Demand pro-jections from these studies are described;
3. Due to uncertainty over what the United States will do in space, four representative demand levels are selected from the STAS and ALS studies. The levels span the potential range of demands for space transportation.

Space transportation is limited in definition to transporting cargo to orbit, and not in-orbit operations or manned spaceflight per se (although manned systems may certainly carry cargo). All transportation demands are assumed to apply only to peacetime operations.

3.2 ESTIMATES OF FUTURE U.S. SPACE TRAFFIC DEMAND

The potential range of future U.S. space launch activity is large. The United States may decide to pull back from space activity and constrain its efforts to largely unmanned science missions and existing DoD operations. Alternatively, the United States may decide to proceed with a full-scale deployment of space-based strategic defenses that would necessitate a major leap in U.S. launch capacity.

Figure 3.1 shows the rough bounds of potential U.S. launch demand for 1995–2010. Historical data were used through 1987, with all vehicles converted to shuttle equivalent flights.[1] From 1987 through 1995, data from the current NASA and DoD manifests were used to indicate planned levels of demand. Beyond 1995 (and beginning even before then), there is a range of demand projections available from the Space Transportation Architecture Studies (STAS) and Advanced Launch System mission models.[2]

3.2.1 The 1988 U.S. Launch Manifest

With the loss of a substantial portion of the shuttle fleet and the prospect of large backlogs of payloads, the Administration moved commercial payloads, such as communica-

[1] The baseline shuttle capacity is 55,000 lb to a 28.5 deg, 110 n mi orbit using 104 percent rated SSMEs (Space Shuttle Main Engines). A standard manifest loading factor is 75 percent with some payloads packed more efficiently than others. Reducing the shuttle capacity by the load factor gives a "real" capacity of about 41,500 lb. This was set as one equivalent shuttle flight. See NASA, *Report to the National Research Council on the NASA Space Station Transportation Study*, NASA Office of Space Flight, NASA Office of Space Station, Washington, D.C., August 3, 1987.

[2] Joint Task Team of NASA and the DoD, *National Space Transportation and Support Study, 1995-2010*, May 1986; and NASA, *National Space Transportation and Support Study, Civil Needs Data Base, Version 2.1*, Vol. I, Executive Summary, NASA Headquarters, Washington, D.C., July 16, 1987.

tions satellites, off the Shuttle and onto ELVs where possible. The Department of Defense increased purchases of Titan launch vehicles already in production and initiated new procurements such as the MLV 1 and 2 to meet the launch needs of military payloads. A renewed market for ELVs thus occurred in the aftermath of the Challenger loss. Figure 3.2 shows the gap between the planned shuttle launch rates before and after the Challenger accident and standdown. The gap between the two lines is essentially the near-term market for new ELVs.

Each of the major launch vehicle manufacturers will have some share of government procurements over the next several years.[3] The Department of Defense prefers ELVs for its needs, which include fewer missions requiring manned presence or shuttle-unique capabilities, whereas NASA makes greater use of the shuttle and a few ELVs for some science missions. In the next few years, the United States will be flying eight types of launch vehicles. Although some of them are closely related (e.g., the Titan 34D and Titan 4), they are nevertheless distinct variants.[4] The Soviet stable of launch vehicles is often cited positively as offering many alternatives for payloads due to its diversity. The new diversity of the U.S. mix compares well with the Soviet mix, if not with Soviet launch rates.[5]

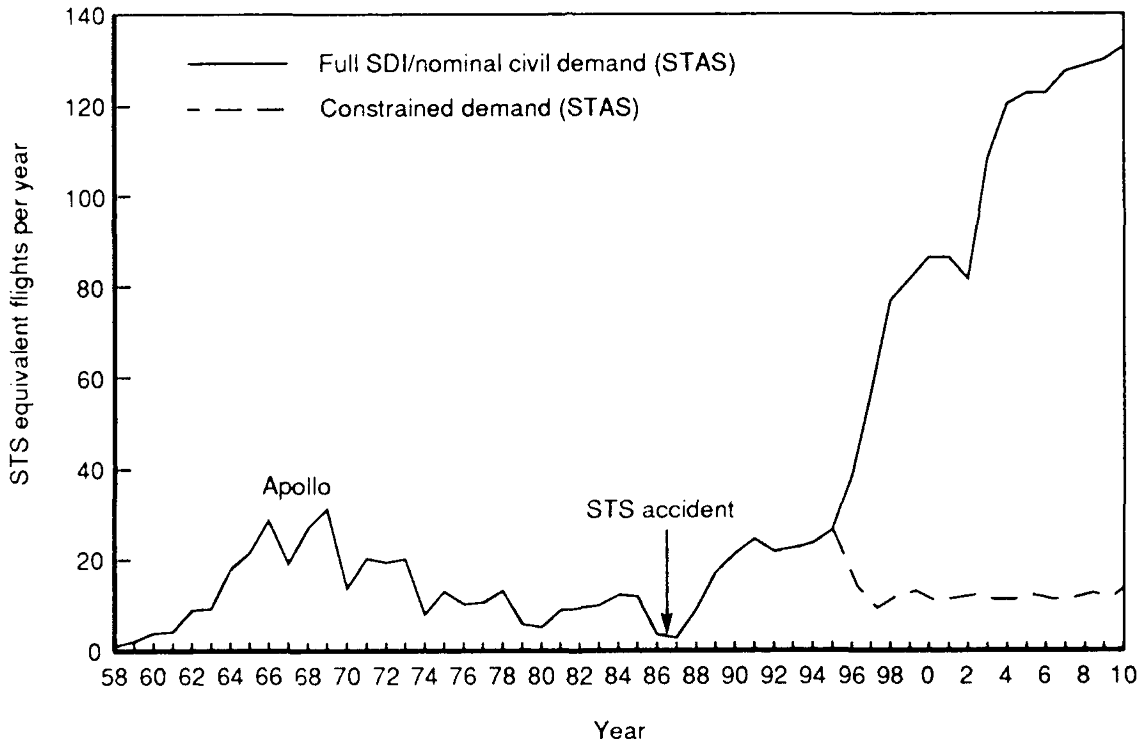


Fig. 3.1—U.S. launch demand ranges

[3] Martin Marietta manufactures the Titans, General Dynamics builds Atlas vehicles, and McDonnell Douglas makes Deltas.

[4] The Titan 4 is a growth version of the Titan 34D, with stretched first and second stages, seven-segment solid rocket motors, and a larger payload fairing.

[5] Current operational Soviet space launch vehicles are the SL-4, -6, -8, -11, and -14 derived from ballistic missile systems and the SL-12, -13, and -16. The SL-X-17 booster, "Energia," is still undergoing flight tests. See Department of Defense, *Soviet Military Power 1988*, U.S. Government Printing Office, Washington, D.C., 1988, pp. 66–67.

The first manifest for future U.S launches following the Challenger accident was released in March 1988.[6] Figure 3.3 depicts the 1988 manifest and shows the relative distribution of STS and ELV usage between the Department of Defense and NASA. Table 3.1 lists the data that make up this figure. Scout launches are not included due to their small size and the limited number of flights planned (e.g., two per year for NASA). The manifest assumes STS flights level off at 14 flights per year by 1994.

3.2.2 Space Transportation Architecture Demand Levels

The Space Transportation Architecture Studies were briefly described in Secs. 2.2.2 and 2.3. The STAS demand projections covered a wide range of possible scenarios for U.S. space efforts. Different levels of NASA and DoD space activity were defined in various combinations with each other. For example, a high level of civil activity, such as missions to Mars, might occur simultaneously with a low level of military activity. Alternatively, a high level of military activity, such as an SDI deployment, might occur with a low level of civil activity. Appendix A describes the STAS combinations in greater detail.

The lowest STAS level averaged about 12 STS equivalent flights per year and was called a constrained demand. The DoD portion of this level was based on continuing only contemporary missions with no new starts. The constrained civil level originally included the space station program, but current program plans and schedule slips from the time of the Challenger accident have eliminated the station from the constrained option. At this level,

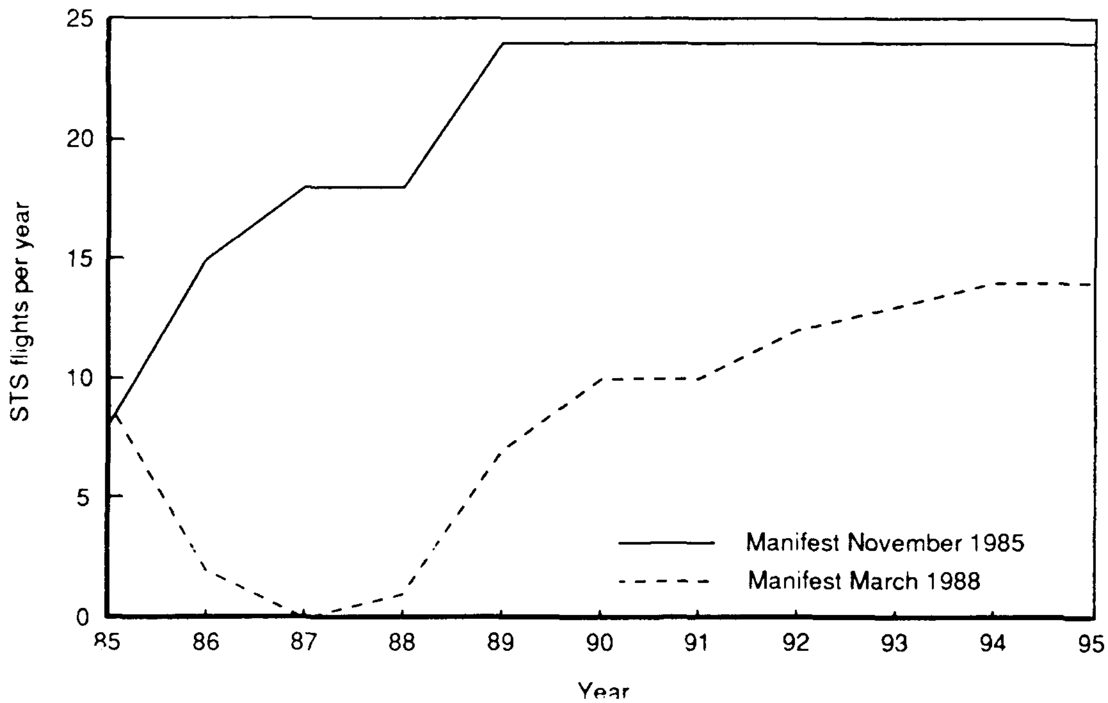
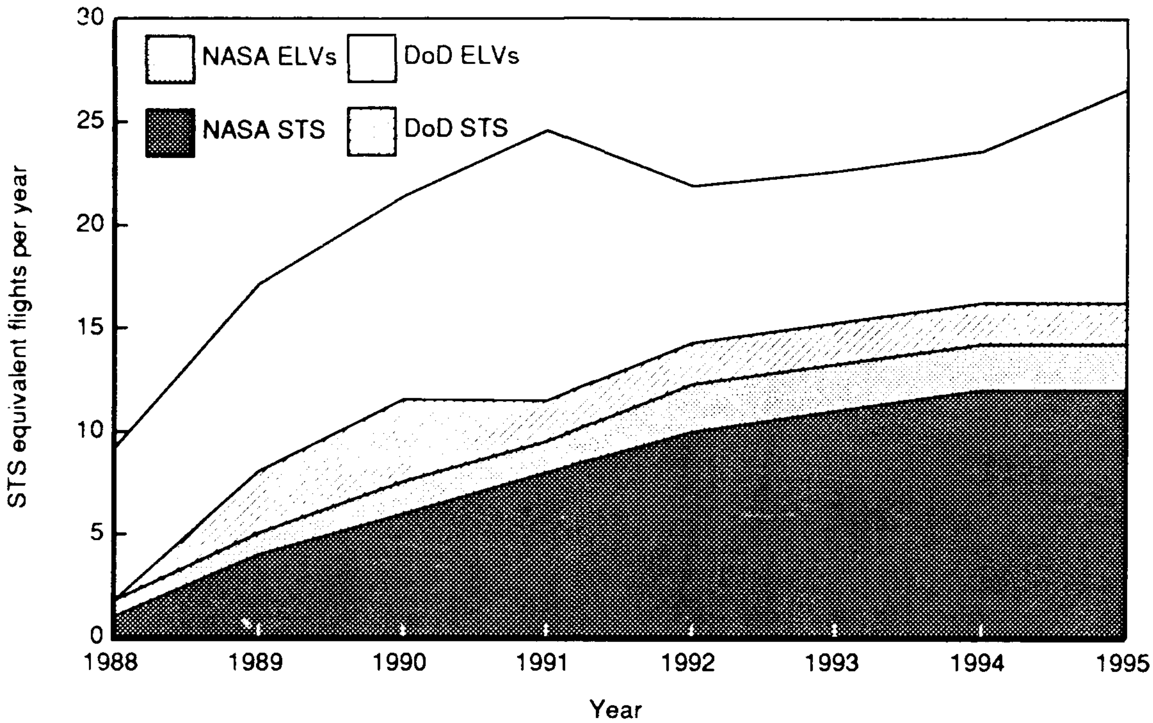


Fig. 3.2—NASA forecasts of STS flights, 1985–1995

[6] NASA, *Payload Flight Assignments NASA Mixed Fleet*, Office of Space Flight, Washington, D.C., March 1988.



SOURCE: NASA.

Fig. 3.3—U.S. manifested flights, 1988–1995

Table 3.1

LAUNCH VEHICLES PLANNED FOR 1988–1995[a]

Vehicle	STS Eqv.	1988	1989	1990	1991	1992	1993	1994	1995
NASA STS	1.0	1	4	6	8	10	11	12	12
DoD STS	1.0	0	3	4	2	2	2	2	2
NASA ELV									
Delta	0.25	2	1	1	1	3	3	3	3
Atlas-Centaur	0.5	0	1	2	1	1	1	1	1
Atlas E/F	0.3	1	1	1	0	1	0	0	0
Titan 34D	0.75	0	0	0	1	1	0	0	0
Titan 4	1.0	0	0	0	0	0	1	1	1
DoD ELV									
MLV 1	0.25	0	4	4	5	4	4	4	4
MLV 2	0.5	0	0	0	3	3	1	1	1
Titan 2	0.3	2	2	2	2	2	2	2	2
Titan 34D	0.75	9	7	6	5	0	0	0	0
Titan 4	0.75	0	3	5	8	6	7	7	11

[a]Although there are some differences between the MLV series and NASA Delta and Atlas vehicles, the differences are not significant in average payload capacities. The DoD Titan 4 is usually launched out of the Western Test Range into high-inclination orbits and thus it has less capacity than NASA Titan 4s launched from the Eastern Test Range into due east orbits. The difference results from the extra energy boost of launching in the direction of the Earth's rotation.

not enough capacity exists to deploy and sustain a station and still perform mandated civil and military tasks.

Nominal levels of STAS demand rose from about 15 equivalent STS flights to about 25 equivalents by 2010. This level of effort would be sufficient to continue current manifests into the future and include some new starts for the Department of Defense as well as the space station program. (See Fig. 3.4). Beyond nominal levels, the STAS models considered various combinations of expanding civil and military demand.

The Mars mission projection included a series of unmanned probes, manned expeditions, and surface camps early in the next century. The bulk of the payload weight projection consists of supporting propellants as well as equipment assembled in Earth orbit for the trips. The Department of Defense is assumed to continue its current level of effort while these missions occur.

The Lunar Base/SDI-KKV projection combined the creation of a permanently manned lunar base with deploying space-based kinetic kill vehicles (KKVs) for strategic defense. The civil effort would be an expansion of currently planned levels of effort, almost dwarfed by DoD needs to deploy and maintain large numbers of space-based interceptors, sensors, and battle-management systems.

A full-scale SDI option expands the deployment of KKVs to include space-based lasers (SBLs) and support systems, while holding to current levels of civil activity. The addition of SBLs after the deployment of KKVs shows up as the "dual-hump" in the Full SDI projection line in Fig. 3.5, with SBL deployments starting around 2003. This demand level was the most ambitious considered in detail by the STAS studies.

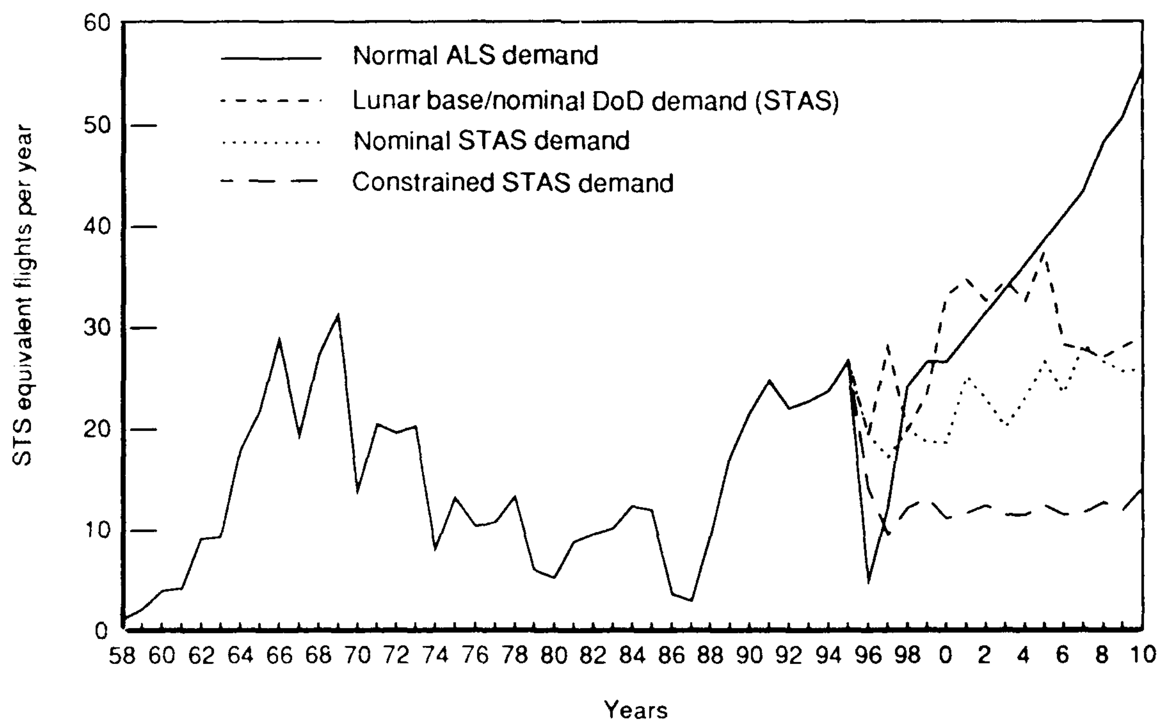


Fig. 3.4—U.S launch demand and nominal models

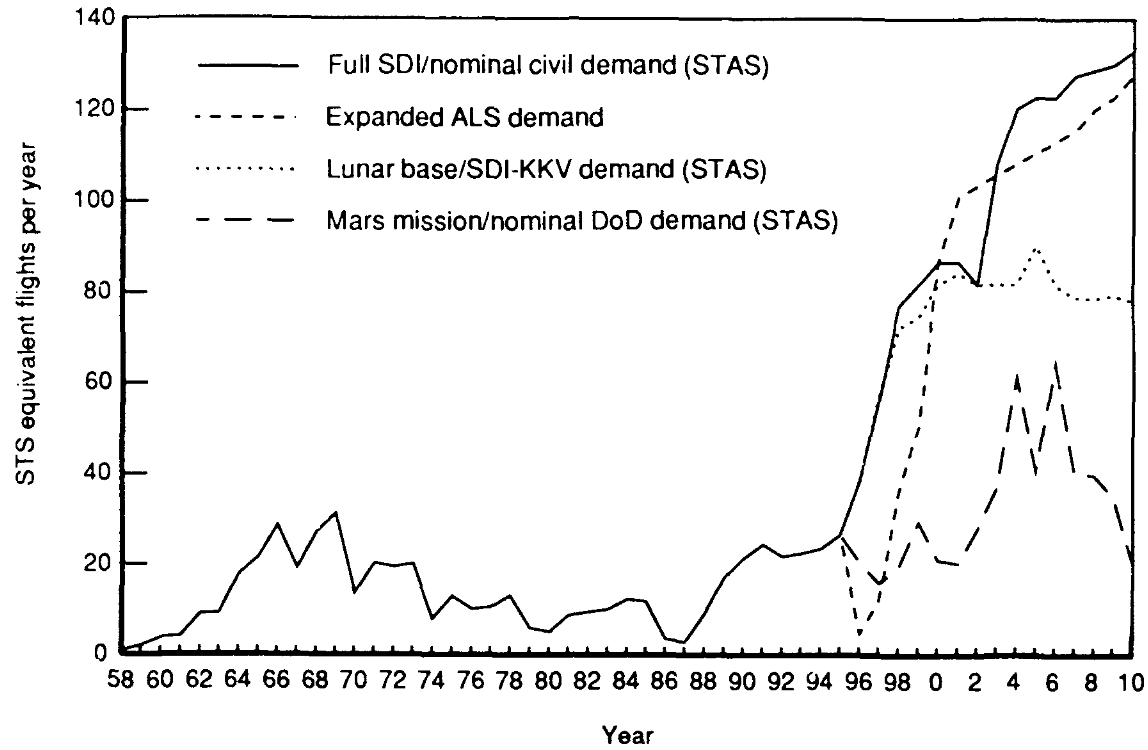


Fig. 3.5—U.S launch demand and expanded STAS/ALS models

3.2.3 Advanced Launch System Demand Levels

The Advanced Launch System program created its own mission models for planning purposes.[7] The models are less a representation of demand than a projection of a desirable level of capability to be carried by vehicles developed in the ALS effort. In 1988, the ALS models assumed an initial vehicle flight in 1996 and two major alternative levels of use. The first level was a "normal" steady growth in traffic, whereas the second was an expansion of that growth to account for major new civil initiatives and/or deployment of SDI systems. The projected payload capacities include not only satellites, but representative upper stages and propellant weights as well. When the lines for the normal and expanded levels are added together, the total line grows to over 5 million pounds per year to low-Earth orbit (LEO) by 2010.

If the ALS demand levels are converted into shuttle equivalents, the total ALS upweight line approaches 140 STS flights per year by 2010. At the normal level of traffic demand, the ALS line approaches 60 STS equivalent flights per year by 2010. The latter level is considerably higher than the the nominal STAS line, as it includes enough capacity to support a lunar base and continue DoD efforts (excluding SDI deployments). Appendix A contains graphs of these demand levels as well as comparisons to past U.S. efforts for perspective.

[7]U.S. Air Force, *Advanced Launch System Requirements Document (Preliminary)*, SD-ALS-R-SRD—v1.00, USAF Space Division, El Segundo, CA, March 3, 1988.

3.2.4 Comparisons of STAS and ALS Demand Levels

The STAS and ALS demand projections can be roughly divided into those commensurate with past experience and those representing dramatic increases in space activity. Figure 3.4 combines several non-SDI demand estimates into a series of charts for comparison with each other and historical levels of effort. In order of increasing space activity, the demand levels are:

- STAS constrained
- STAS nominal
- STAS lunar base/nominal DoD
- Normal ALS

This figure also helps put the non-SDI models into perspective with the 1988–95 manifest. The large dip at the end of the historical data results from the losses of the Challenger, Titan, and Atlas launch vehicles in 1986. With the revival of flights in the early 1990s, space traffic upweights climb to levels comparable with the Apollo effort.

Beyond the manifested flights, there are a range of options from very constrained, through a nominal effort, to continued real growth resulting in a lunar base early in the next century. The gap between manifest levels and the normal ALS line in the mid-1990s is an artifact of the ALS having a 1996 IOC date. In actuality, there would be some transition plan from the current mix of shuttles and ELVs to a mix including (or dominated by) the ALS. Even after assuming flights to fill in the gap, the steady increase is still dramatic.

Scenarios for manned Mars missions and SDI deployments call for demand levels significantly above past experiences. The demand projections for these operations are shown in Fig. 3.5, which compares the STAS and ALS projections with historical demand levels and the 1988 manifests. In order of increasing activity, there are four combinations of civil and military space traffic:

- STAS Mars mission/nominal DoD
- STAS lunar base/SDI-KKV deployment
- Expanded ALS
- STAS nominal civil/full SDI deployment

The expanded ALS and STAS full SDI projections are roughly comparable, which should not be surprising as the ALS estimate was made after the STAS effort. All of the projections imply a new generation or type of launch vehicle to sustain traffic levels which are factors of three to seven above past experience.

3.3 CREATION OF FOUR BASELINE DEMAND SCENARIOS

The demand projections shown above for post-1995 activity are illustrative of U.S. options over the next 20 years and are not program plans for implementation. Moving from these varying demand levels to launch vehicle mixes is a more difficult problem. It would be cumbersome to examine each of the alternatives in detail and then allocate launch vehicles to them (and in many cases, the vehicles do not yet exist). A detailed allocation would require knowledge of specific payload sizes, weights, orbital destinations, and other constraints. Such detail is available in the STAS models, but only in spreadsheets constituting volumes of data. Using such detail can be misleading as payload requirements undergo rapid change as programs progress to flight, so a true manifesting exercise would soon be obsolete.

Because the purpose of this study is to clarify alternatives available to the United States in pursuing different national goals and associated traffic demands, attention is paid to the gross levels of varying demand and the major launch vehicle alternatives. This in turn means focusing on aggregate demand levels and vehicle capacities as opposed to manifesting and packing individual flights. One motive for this, aside from simplifying the selection of launch vehicle mixes, is to identify major discriminators between the vehicle mixes chosen at different demand levels. A few percent difference in packing efficiencies, payload margins, or costs per pound are lost in the uncertainties of the estimates that can be made today.

An additional important question is what vehicle mixes are preferable for the United States when specific future demand levels are unknown. If a specific demand level and payload mix would materialize with certainty, planning a set of cost-effective launch vehicles would be fairly straightforward. The real world is not like that, however, and choices still need to be made. Building vehicles that can handle the largest credible demand is one response, but not necessarily the best one.

Thus there is a need to simplify the many alternative demands into a representative set of aggregate demands that will illustrate the most significant tradeoffs in planning future space transportation systems to low Earth orbit. The STAS and ALS demands can be grouped into four general categories:

1. Constrained demand: total U.S. launch rates of about 10–15 STS equivalent flights per year.
2. Nominal demand: total flight rates of about 20–30 STS equivalent flights per year, rising to about 60 by 2010.
3. Nominal DoD/expanded civil demand: peak flight rates of 35–70 STS equivalent flights per year.
4. Nominal civil/expanded DoD demand (e.g., Strategic Defense Initiative deployment): a steady rise to 120–140 STS equivalent flights per year.

It seemed implausible that the United States would engage in both an expanded civil and military space effort at the same time. This option was not included in the STAS studies and is not included here.

The constrained demand case can be directly represented by the STAS constrained demand level. Its relation to the 1988 manifests is shown in Fig. 3.6. This situation might result from a cancellation of the space station program and DoD new starts due to budgetary constraints.

The nominal demand case can be represented by the STAS nominal demand level. Figure 3.7 shows this as a continuation of the level of effort shown by the current manifest. The demand level is uneven, requiring some flexibility year-to-year in the use of launch vehicles.

The "normal" ALS line is a more ambitious level of effort that could cover an expanding civil space effort, such as a permanent lunar base. Thus, for the case of a nominal DoD/expanded civil demand, the Normal ALS projection was used. The transition from the 1988 manifest to the ALS line was filled in as shown in Fig. 3.8 by assuming there would be a smooth handover from current demand levels to an expanding civil effort.

The nominal civil/expanded DoD case can be represented by either the ALS expanded model projection or by the STAS full SDI deployment level. The latter was chosen because it leveled off somewhat higher than the ALS line and its curvature would require flexibility in the year-to-year use of launch vehicles. Again, the transition from the 1988 manifest to the STAS model was filled in, as shown in Fig. 3.9.

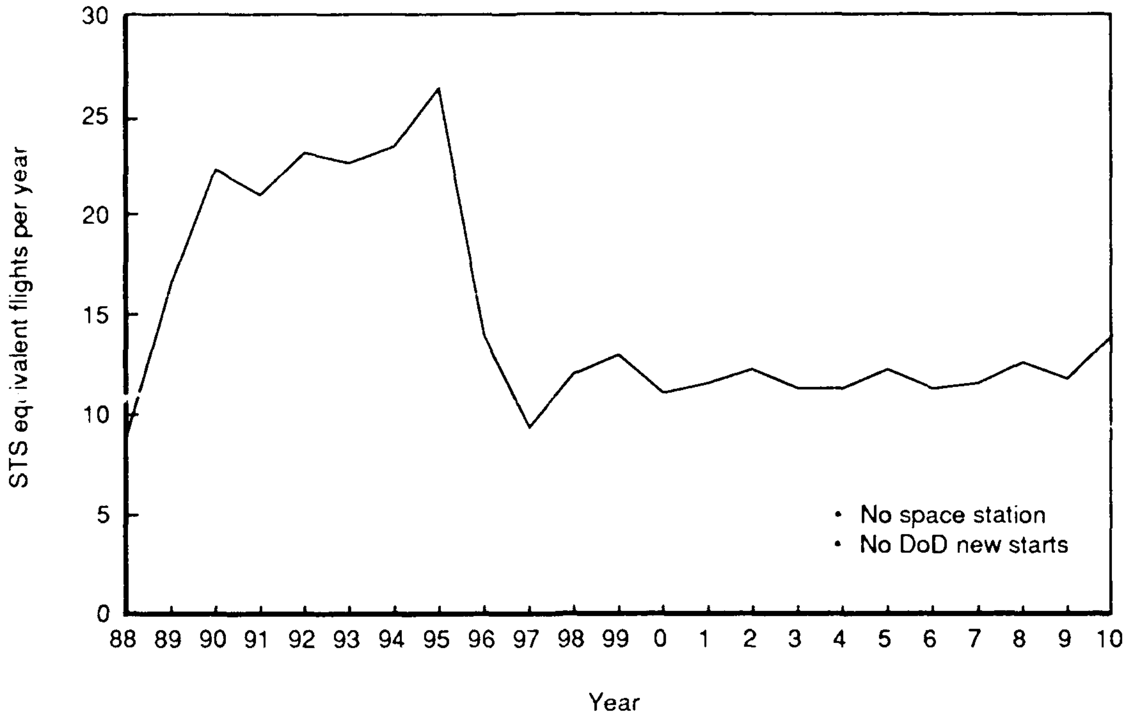


Fig. 3.6—Constrained demand baseline

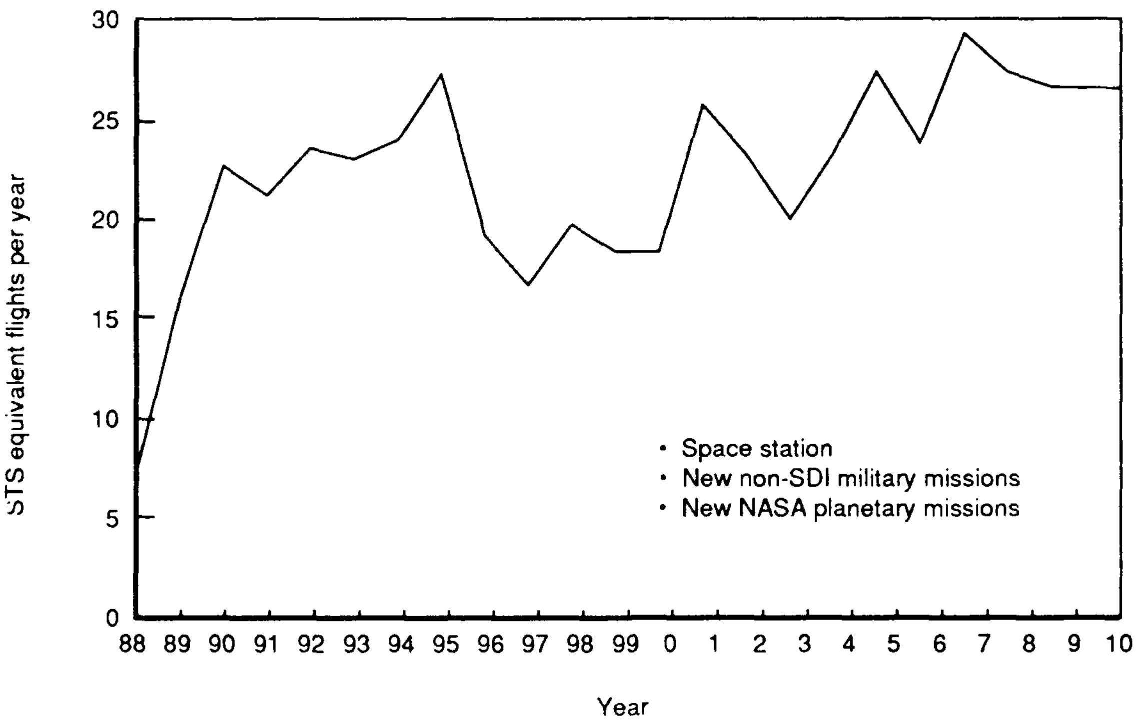


Fig. 3.7—Nominal demand baseline

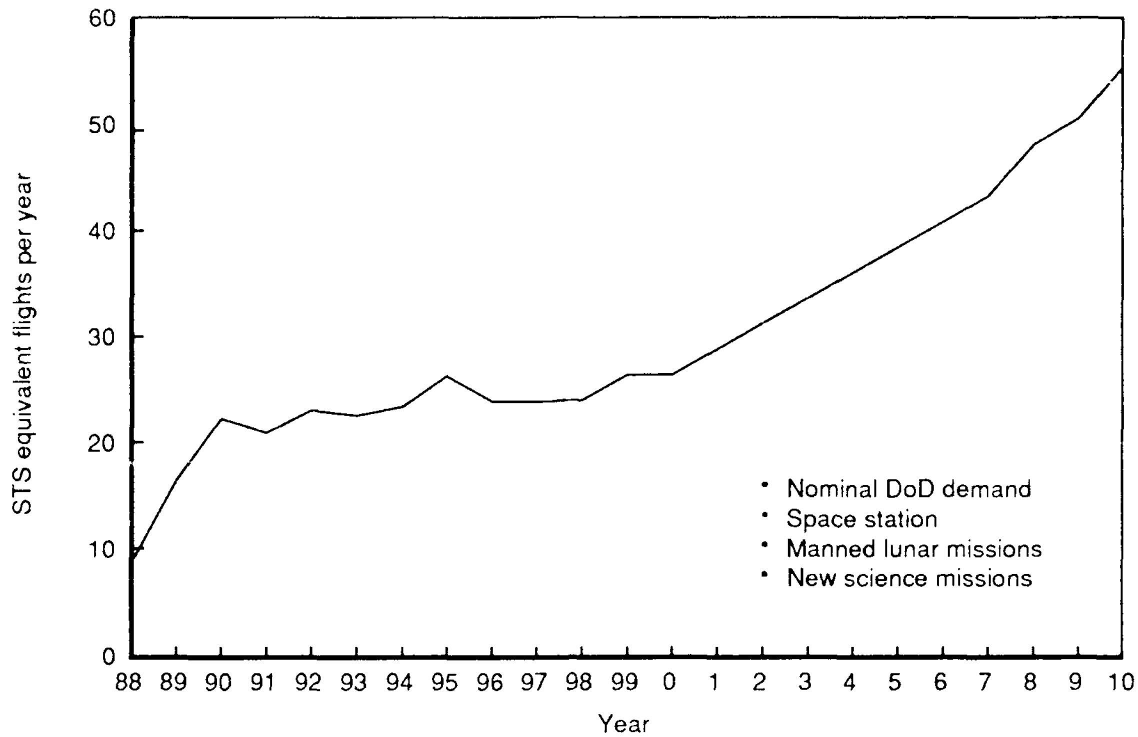


Fig. 3.8—Expanded civil demand baseline

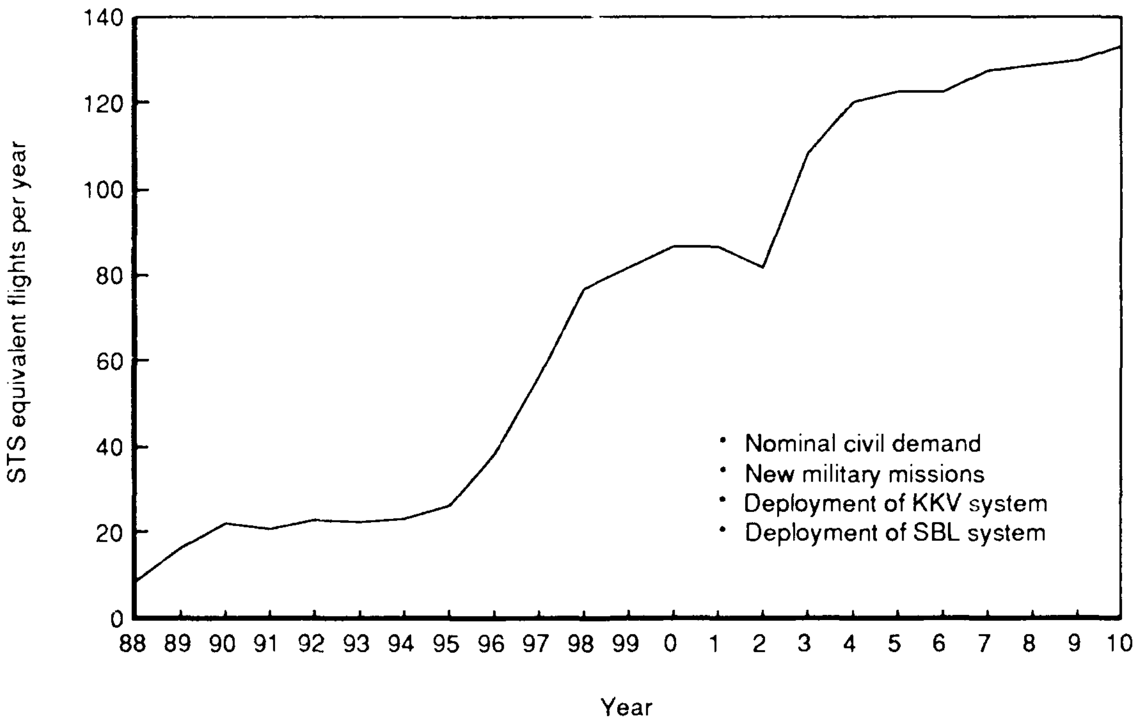


Fig. 3.9—Expanded DoD demand baseline

These four demand categories spanned the range of future U.S. activity as alternative baseline demand projections. Specific government-defined demands were selected to represent each category:

- Constrained demand: STAS constrained demand
- Nominal demand: STAS nominal demand
- Nominal DoD/expanded civil demand: ALS normal demand
- Nominal civil/expanded DoD demand: STAS full SDI demand

The next step is to define the alternative mixes of launch vehicles that can meet these demand levels. This is the subject of Sec. IV.

IV. ALTERNATIVE U.S. LAUNCH VEHICLE OPTIONS

4.1 APPROACH

The purpose of this section is to assess the major launch vehicle options open to the United States for the next two decades. The section summarizes the major performance and cost factors affecting the appropriate mix of launch vehicles for different levels of demand. The assessment consists of three major steps:

1. Compare differing combinations of existing and proposed launch vehicles with the representative demand levels defined in Sec. 3.3;
2. Modify existing and proposed launch vehicle combinations to match the representative demand levels;
3. Estimate the costs and performance risks (e.g., vehicle accidents) associated with applicable launch vehicle mixes at each demand level.

Launch vehicle costs, such as development, production, and operations and support efforts, over the 1990–2010 period were combined with payload costs to provide rough estimates of the total budgetary impact of each launch vehicle mix and demand level. Likely total payload losses and schedule delays due to launch failure were estimated for the vehicles in each launch mix.

Institutional and political issues will be considered in Sec. V. New launch systems are assumed to be government developed, but are *not* necessarily government owned and operated. Supporting background material on launch vehicles, cost and reliability issues, and available budgets can be found in Apps. B and D.

Top-level recommendations on the "best" launch vehicle mix are made for each demand level. However, the recommendations assume the demand level itself is known with some certainty. The more realistic case is one in which the future demand level is uncertain. Policy decisions to initiate future traffic demands have not yet been made and these decisions depend somewhat on available launch vehicles. Possible demand-level decisions are discussed in the context of projected times for launch vehicle decisions. (Subsequent interviews with senior decisionmakers clarified, and in some cases altered, these recommendations.)

4.2 BASELINE DEMANDS AND POTENTIAL LAUNCH VEHICLE MIXES

Figure 4.1 shows the 1988 manifest of shuttle and ELV flights being continued into the future without change (denoted by the solid line). Table 4.1 shows the launch vehicle usage levels per year, assumed constant for 1996–2010. For comparison, the four baseline demand levels defined in Sec. 3.3 are also shown. Continuing current levels of effort could leave the United States with either a large overcapacity or shortfall of launch capability depending on which level of demand occurs.

These usage levels are more than sufficient for a constrained demand, and comparable to the needs of a nominal demand (with some over and undercapacity at different years). These levels do not, however, support either the expanded civil demand or expanded DoD demand cases.

If a Shuttle-C vehicle were added to the current mix of STS and ELV launchers, the first flight could occur by 1994. Each Shuttle-C flight is assumed to have an upweight capacity of about 120,000 lb, which is approximately 2.75 STS equivalents (after accounting for nonpay-

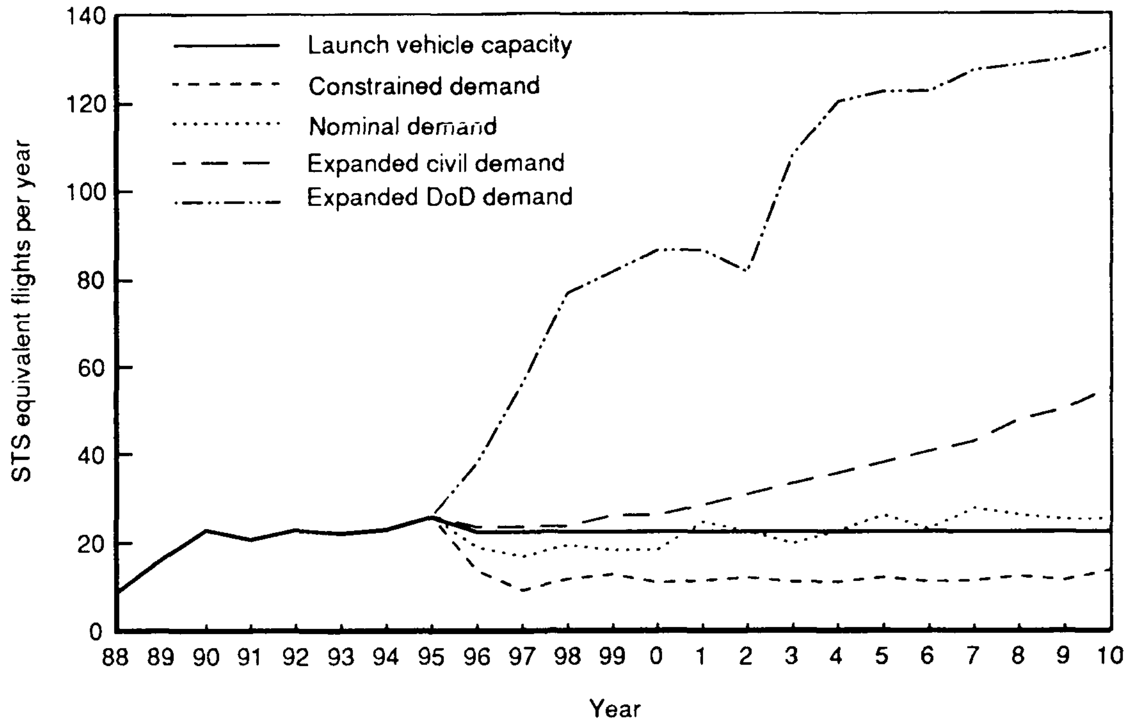


Fig. 4.1—Current STS/ELVs vs. alternative demand levels

Table 4.1

NEAR-TERM STS/ELV USAGE LEVELS

Launch Vehicle	Flights/ Year
NASA STS	12
DoD STS	2
Civil ELVs	
Delta	2
Atlas-Centaur	1
Titan 34D/4	1
DoD ELVs	
MLV 1	2
MLV 2	1
Titan 4	8

load internal support structures). Three flights per year (with a capacity of up to six) is commonly cited as the number needed to support deployment and operation of the space station and other heavy-lift missions. The heavy-lift missions are mostly civil, focused on the space station and possibly planetary science flights, but large SDI experiments may be included. Operations at high flight rates (above about five per year) are limited by the number of shuttle-compatible launch complexes (i.e., two at the Kennedy Space Center) and processing facilities.

The Shuttle-C program would not continue indefinitely, but would likely be phased out after the turn of the century, about the time a new manned vehicle (e.g., shuttle II or the National Aerospace Plane) could be available to take over manned spaceflights from the shuttle. The Shuttle-C would have served its central purpose in the space station program and it would not be supportable without continuing major space shuttle component production lines.

Given the high capacities required by an expanding DoD demand, it seems a heavy-lift vehicle (HLV) from the ALS program would be required. Heavy-lift vehicles are typically designed to lift approximately 150,000 lb to LEO, which is about 3.5 STS equivalents. Assuming a first flight in 1998 and the availability of at least three dedicated launch sites, a flight rate of up to 21 flights per year could be sustained. If a near-term SDI deployment was selected, however, the ALS effort would have to be accelerated to provide timely capacity. The addition of a Shuttle-C to the ALS HLV capacity does not help significantly in the case of expanded DoD demand. The Shuttle-C provides an earlier HLV capacity, but not enough to meet the rapid requirements of an SDI deployment given an ALS HLV IOC of 1998.

Leaving aside the extreme cases of constrained demand or an SDI deployment for the moment, what might be done to match launch vehicles more closely to a nominal demand level? The most obvious solution to future undercapacities would be to buy more ELVs, presumably from emerging commercial launch vehicle companies (e.g., commercial Deltas, Atlases, and Titan 34Ds). Figure 4.2 shows how the capacity level has increased with purchases of two additional Deltas, Atlases, and Titan 34Ds each per year, meeting almost all of the peaks in the nominal demand line at the expense of overcapacity in the late 1990s. The expanded civil line still grows beyond this mix by the turn of the century, however.

The next obvious modification would be to add an additional shuttle orbiter to increase the STS flight rate, thus expanding the shuttle fleet to five, its originally intended size in the late 1970s. The replacement shuttle (OV-105) is scheduled to be available by 1991, and an OV-106 could be available in 1996.[1] The capacity line of Fig. 4.3 assumes a conservative flight rate of three missions per year for the additional vehicle. The addition of another orbiter and more ELVs clearly covers all of the nominal demand level and delays the need for new vehicles until 2001 in the expanded civil demand case.

Figure 4.4 shows the case of a adding a "low flight-rate" ALS HLV to the current STS/ELV mix. The first flight is still in 1998, but increases in the flight rate are slow, starting from two per year and ending at about eight to ten per year. This requires less in the way of new ground facilities, as well as a lower production rate. Although the ALS HLV's payload capacity is large, and thus difficult to "fine tune" to demand, its flight rate can be adjusted to roughly match an expanding level of civil demand.

4.3 SELECTING LAUNCH VEHICLE MIXES APPLICABLE TO BASELINE DEMANDS

In the above discussion, seven different launch vehicle mixes were discussed and compared with the four baseline demand levels. The mixes were:

[1]It takes about five years to build a shuttle orbiter, primarily because of the procurement of long lead-time items such as the titanium forgings for the aft thrust structure housing the three main engines.

- Current STS/ELV levels as a base for all options
- Adding more ELVs
- More ELVs and a five-orbiter shuttle fleet
- Adding a Shuttle-C
- Adding an ALS HLV
- Adding a Shuttle-C and ALS HLV
- Adding a low flight rate ALS HLV

The launch vehicle mixes were not applicable to all demand levels as there was usually a large undercapacity or overcapacity. Each demand level was examined to find which vehicle mixes were appropriate from a capacity standpoint. Next, some modifications were defined to bring applicable mixes closer in line with the baseline demands.

Figure 4.5 projects how launch costs per pound vary as a function of the number of pounds placed in orbit by the shuttle, Delta 2, and Titan 4 launch vehicles.[2] The projections include production learning curve effects and economies of scale for increased flight rates. To simplify cost calculations for a mix of vehicles, however, average costs per flight were assumed for current launch vehicles, as shown in Table 4.2. Figure 4.5 shows how the constant cost per flight estimates compare with more detailed projections for the same vehicles. Learning curve and rate effects were deleted not only for current vehicles but for the recurring costs of new vehicles as well. The recurring cost estimates are conservative and may decline with future advances in ground processing productivity.

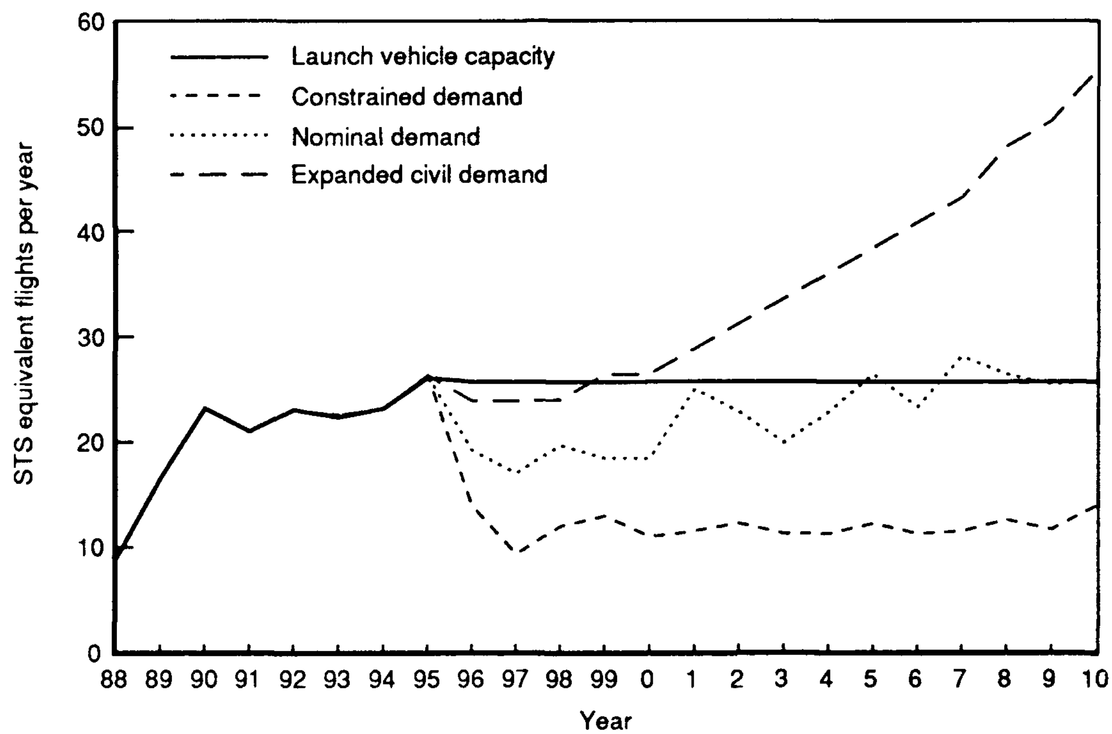


Fig. 4.2—Current STS/ELVs and more ELVs

[2]See App. B.

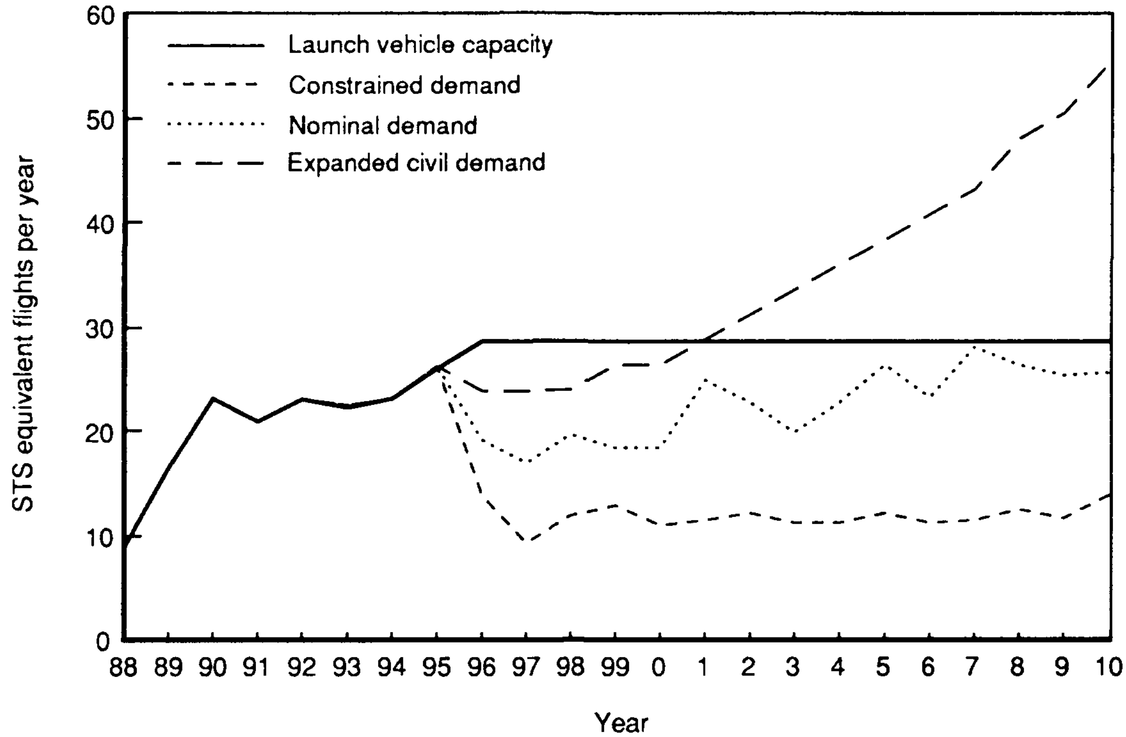


Fig. 4.3—Current STS/ELVs, more ELVs, and a fifth orbiter

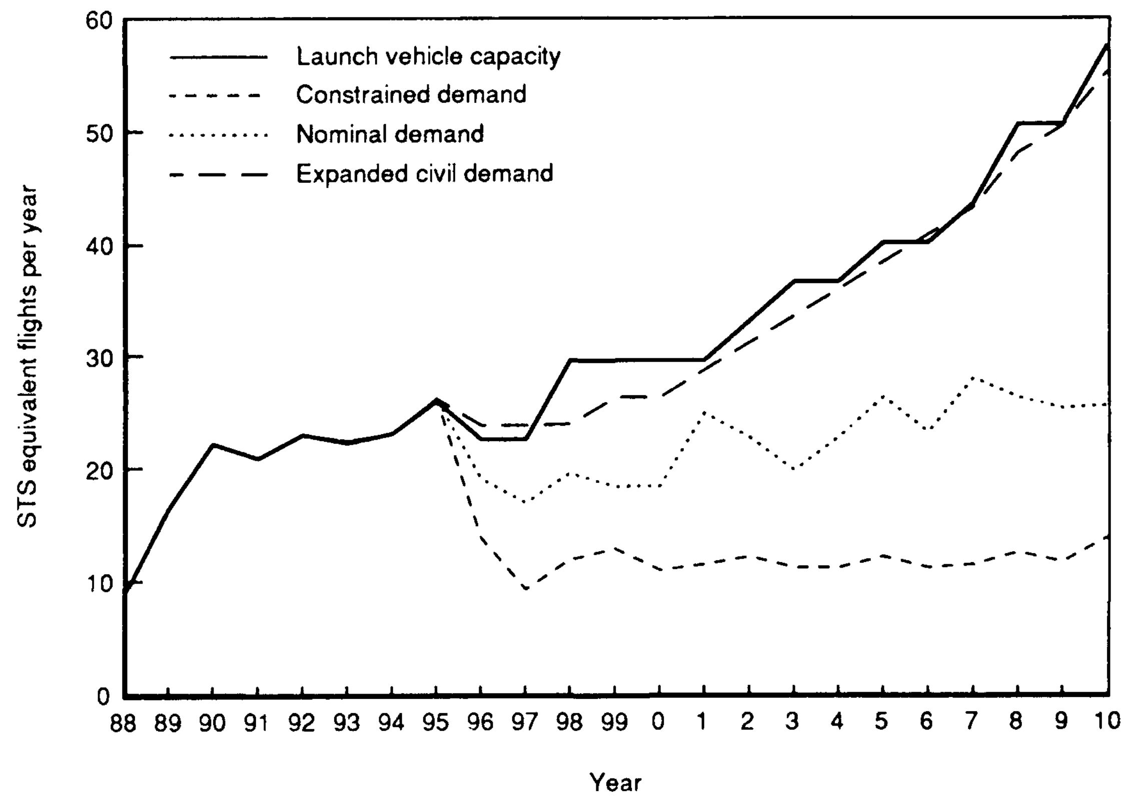


Fig. 4.4—Current STS/ELVs plus low flight rate ALS HLV

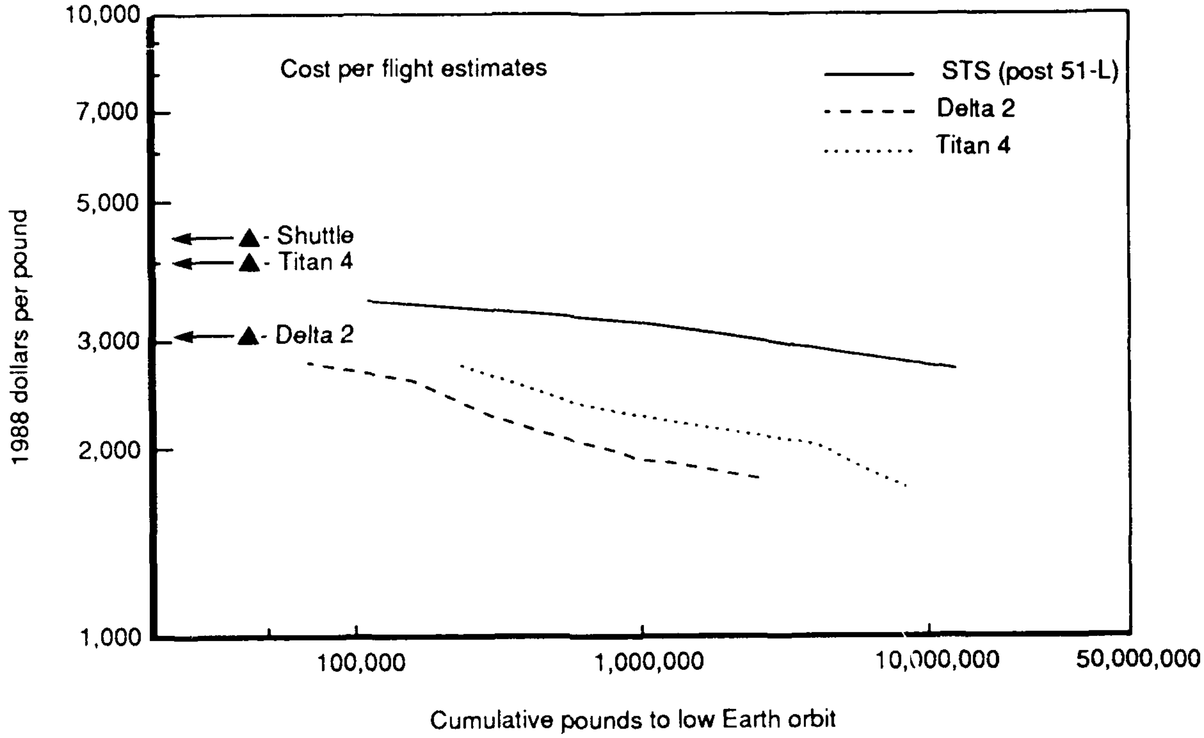


Fig. 4.5—Launch costs—existing systems

Table 4.2

BASELINE LAUNCH VEHICLE COSTS

Launch Vehicle	Cost Per Flight	Cost Per Payload Pound
STS	$245 million[a]	$4,400
Delta	$35 million[b]	$3,100
Atlas-Centaur	$71 million	$4,700
Titan 34D/4	$163 million	$4,200
Titan 2	$48 million	$9,200
Atlas E/F	$60 million	$11,000

[a]Congressional Budget Office, *The NASA Program in the 1990s and Beyond*, U.S. Government Printing Office, Washington, D.C., May 1988; and Congressional Budget Office, *Setting Space Transportation Policy for the 1990s*, U.S. Government Printing Office, Washington, D.C., October 1986.

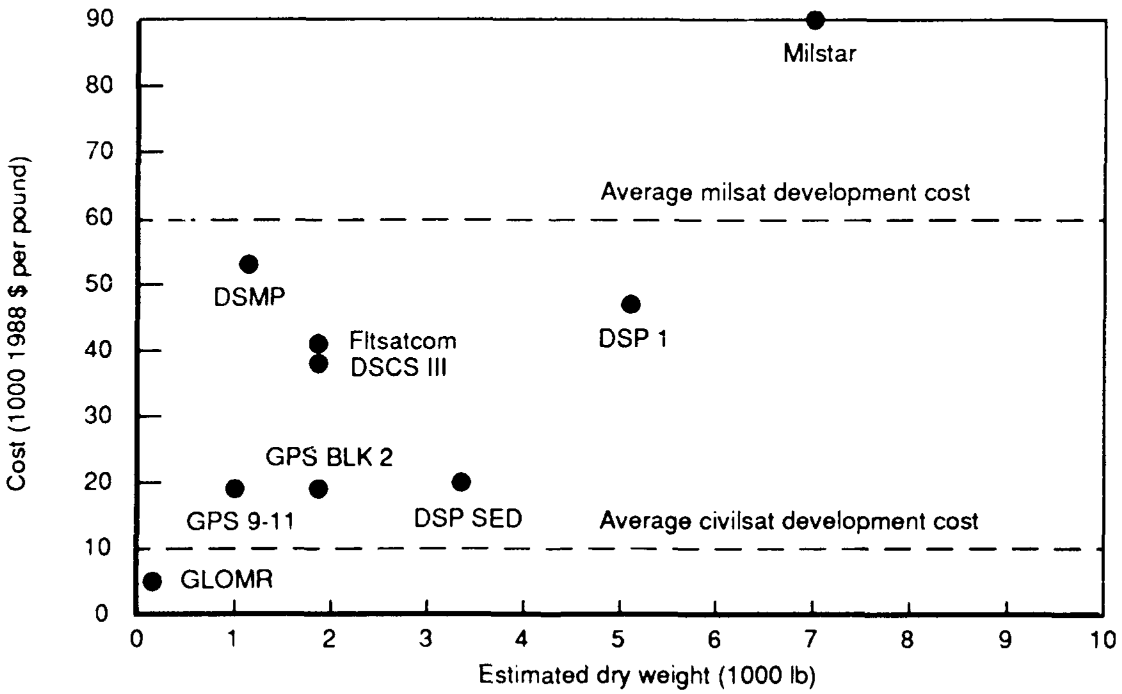
[b]The ELV cost estimates are from a letter to Robert K. Dawson, Associate Director for Natural Resources, Energy and Science, at the Office of Management and Budget, from Dale Myers, Deputy Administrator, National Aeronautics and Space Administration, January 20, 1988.

Payload costs are a more difficult problem as they can vary widely.[3] A simplification was thus to assume a constant average cost per payload pound, allowing a direct comparison of the relative levels of effort for different demands and preserving a sense of the magnitude of payload costs relative to launch costs. Based on separate analysis, an average of payload cost of $10,000 per pound was assumed.[4] Some care is required in using this figure in that it represents the average cost per pound for a fully manifested launch vehicle. Average costs for satellites per se are about $35,000 per pound, but when representative weights for upper stages, payload integration adapters, and fuel are factored in, the overall cost per pound drops for payload as a whole (in which the satellite itself is only one element).[5] Figure 4.6 shows several examples of military satellite costs as a function of their dry weight.

Appendexes B and D provide a more detailed discussion of these assumptions and estimates.

4.3.1 Launch Vehicles for a Constrained Demand

In the case of constrained demand, the problem is overcapacity in all the mixes examined so far. Consequently, three alternative launch vehicle mixes will be examined to match the low demand: (1) use of fewer STS and ELV flights, (2) use of only STS flights after 1995 (the end of the 1988 manifest), and (3) use of only ELVs after 1995. The uncertainty range about the demand was one STS equivalent flight, so the demand could be matched fairly closely.



SOURCE: Aerospace Corporation, DARPA, USAF, *Aviation Week.*

Fig. 4.6—Military satellite costs

[3]See App. D.2 and D.3
[4]Ibid.
[5]Ibid.

Assuming that a mixed fleet of STS and ELV flights would still be maintained after 1995, a constrained demand mix was defined as shown in Table 4.3 below. This results in a sharp drop-off in launch activity after 1995 due to the transition from the 1988 manifest to the lower level of the constrained demand baseline.

Table 4.3

CONSTRAINED STS/ELVs USAGE LEVELS

Launch Vehicle	Flights/ Year
NASA STS	7–8
DoD STS	0
Civil ELVs	
Delta	0
Atlas-Centaur	0
Titan 34D/4	1
DoD ELVs	
MLV 1	2
MLV 2	1[a]
Titan 4	4–8

[a]One every other year.

The mixed fleet might be abandoned with a reversion to an all shuttle fleet after 1995. For a constrained demand level, 12 to 14 STS flights per year would suffice. Of course, users of space transportation might prefer a more diverse means of access to space. Alternatively, it is possible the shuttle program would be halted and only ELVs used to meet a low demand for space transportation, implying that the United States would forgo manned access to space. A usage level of 10 Deltas, 6–7 Atlas-Centaurs, and 8–11 Titan 4s per year would suffice to meet the constrained demand baseline.

The next question after verifying that various vehicle mixes can be closely matched to a constrained demand is to ask how the alternatives compare on cost. From the period covered by the 1988 manifests, both payload and launch vehicle costs drop from about $15 billion per year to about $8 billion. Figure 4.7 compares the launch vehicle costs of the all-STS, STS/ELV mix, and all-ELV options (post-1995). In each case, the payload costs are the same since the constrained baseline demand remains unchanged. In this comparison, the all-STS option is the most expensive whereas the all-ELV case is the least expensive. The mix of STS and ELVs is slightly cheaper than the all-STS case. This mix could be seen as advantageous given requirements such as continued manned access to space and the preservation of a diverse number of launch vehicles. The importance of both a diverse launch vehicle mix and excess capacity are discussed further in App. D.

4.3.2 Launch Vehicles for a Nominal Demand

In the case of nominal demand, the problems in vehicle mixes are a combination of overcapacity in some options and the need to adapt to year-to-year changes. A straight line

continuation of the STS and ELVs in use in the early 1990s would be the mix shown in Table 4.4.

The obvious problem with a level continuation of launch vehicles is that demand in some years will exceed the planned procurement rate. Rather than increasing the overcapacity found in other years, one solution would be to purchase additional ELVs only as needed. It was assumed that additional commercial Deltas, Atlas-Centaurs, and Titans 34Ds could be bought for the same price as similar government launch vehicles. The needed purchases are small, ranging from one to four of each type in any particular year, with the result that the launch vehicle supply would closely track the baseline nominal demand.

An alternative option is to add Shuttle-C flights, at a rate of two per year, beginning in 1995. This would provide a heavy-lift capability and add substantial launch capacity to the base of STS/ELV buys (as shown in Table 4.4). The addition of the Shuttle-C easily meets

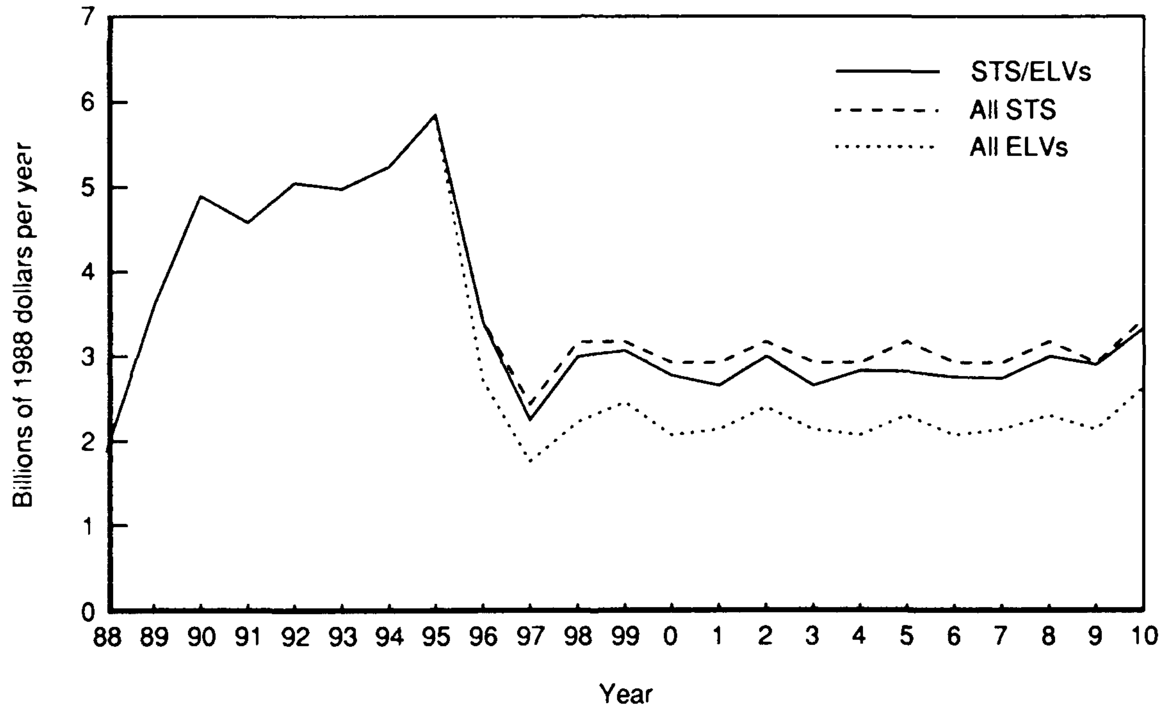


Fig. 4.7—Constrained demand/launch vehicle options

Table 4.4

CURRENT STS/ELVs CONTINUED FOR A NOMINAL DEMAND

Launch Vehicle	Flights/ Year
STS	14
Delta	4
Atlas-Centaur	2
Titan 34D/4	9

the nominal demand level, but results in a large overcapacity. Flying at a rate of less than twice a year is unlikely to be feasible due to constraints on maintaining launch crew proficiencies and production lines for unique Shuttle-C components. It would also be difficult to use Shuttle-C flights to supplant conventional ELVs. The efficient manifesting of multiple payloads has already proved difficult with the shuttle and the Shuttle-C's larger payload envelope would make those difficulties even greater.[6] The utility of Shuttle-C to a nominal demand would likely have to come from unique capabilities (e.g., reducing the number of required space station flights or extending the life of the shuttle fleet) as opposed to its lift capacity alone.

Figure 4.8 compares the three alternatives discussed above for a nominal demand. A base of existing STS and ELV capabilities can be augmented in specific years by procuring additional ELVs to meet small variations in demand. Alternatively, a Shuttle-C making only two flights per year would add a heavy-lift capacity that could meet or easily exceed all of the nominal demand. The Shuttle-C flight rate could also be increased to reduce the number of manned shuttle flights and thus extend the operational life of the orbiters.

The cost of adding a Shuttle-C, such as shown in Fig. 4.9, involves more than estimating a cost per flight and multiplying by the number of flights per year. The cost of having the Shuttle-C option must include the costs of design, development, test and evaluation (DDT&E), production of expendable elements, and operating and support (O&S) costs per flight. Figure 4.10 is a projection of Shuttle-C costs per pound as a function of payload weight placed in orbit.[7] The upper line includes the amortization of all costs, whereas the lower line excludes estimated DDT&E costs. (DDT&E costs were treated as sunk for the STS and ELVs already considered.) As flights accumulate, fixed costs are distributed over a wider base and the average cost per pound drops. The Shuttle-C recurring cost of $4300 per pound is shown as corresponding to the level reached after nonrecurring costs have been amortized.

Shuttle-C development cost was assumed as $1.224 billion spread over the years 1990-1994.[8] A rough estimate of production costs is shown Table 4.5. The costs were assumed to be constant to simplify cost calculations for launch mixes. In contrast, learning curve effects were included in Fig. 4.10. A rough estimate for operating and support costs is shown in Table 4.6.

Production and O&S costs total $520 million for a 120,000 pounds-to-orbit capability (which will be somewhat less in reality because of payload packing problems). This comes out to about $4300 per pound which compares closely with Titan 4 and shuttle cost estimates of $4200 and $4400 per pound, respectively. In comparison with Fig. 4.10, $4300 per pound corresponds to mature Shuttle-C operations and is thus likely to be an optimistic cost.

Figure 4.11 shows the comparative costs for each of the three applicable launch vehicle mixes in the nominal demand case. The continuation of STS and ELV buys is the least costly option, but some demand is unmet. The addition of some ELVs allows the United States to meet demand peaks and results in a relatively minor cost increase. The Shuttle-C is the most expensive, yet it also provides the greatest additional capacity. In many years, that additional capacity is not fully utilized and other operational benefits would be needed to justify it.[9] Two flights a year adds about a billion dollars per year in expenses out of a total of $6 billion per year in launch vehicle costs.

[6]Satellites have different orbital destinations, schedule requirements, and physical incompatibilities that makes placing multiple satellites on one flight difficult. In addition, commercial operators are reluctant to risk several of their payloads on single, large flights.

[7]See App. B.

[8]Private communications with Rockwell International, STS Division, September 1987 and July 1988.

[9]Shuttle-C operational benefits could include reducing the number of flights required to deploy the space station, saving assembly times for crew members on-orbit by launching preassembled components, and providing a test bed for shuttle components.

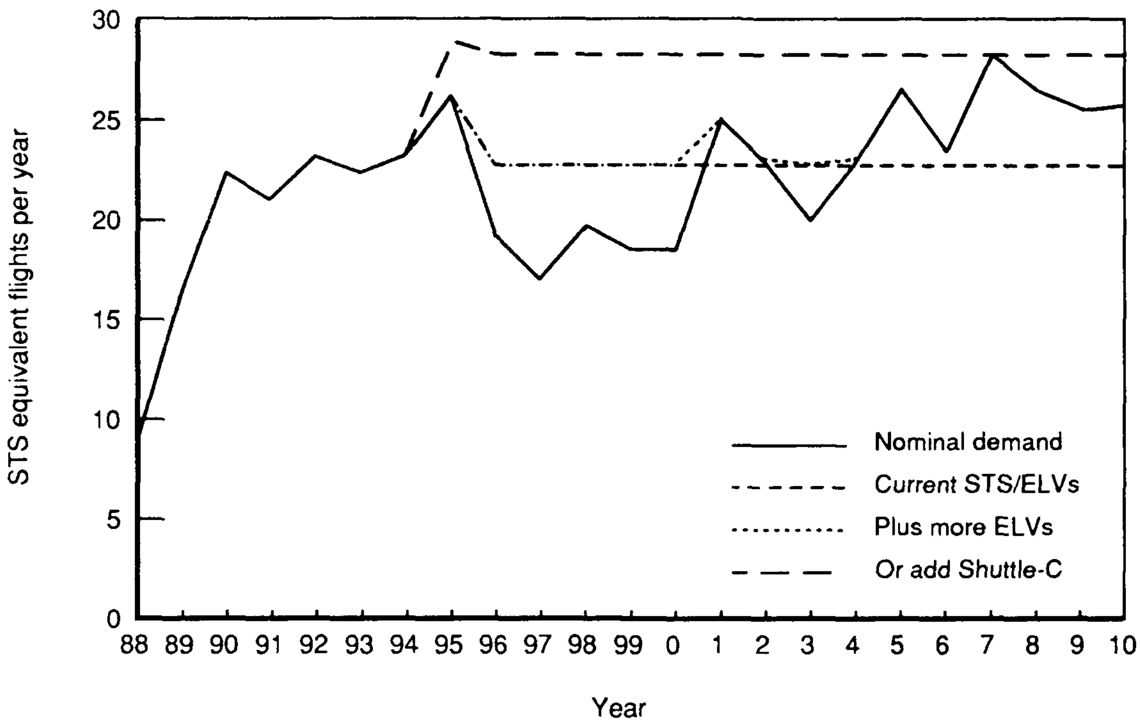
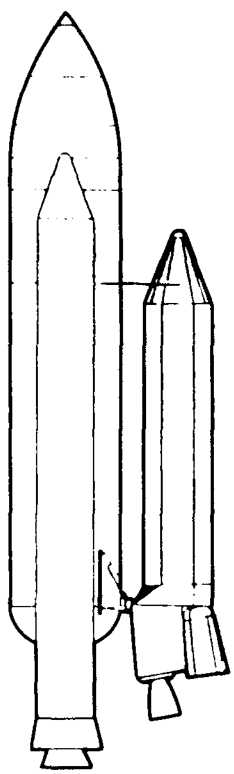


Fig. 4.8—Nominal demand and applicable launch mixes



SOURCE: NASA.

- Standard 4-segment solid rocket boosters (reusable)
- Standard external tank (expendable)
- Orbiter boattail (expendable)
  - 2 SSMEs (remove SSME #1)
  - Remove vertical stabilizer
  - Remove body flap
  - Cap SSME #1 feedlines
  - OMS pods (do not install OMEs, RCS tanks and 4 RCS thrusters/pod)
  - RCS performs circularization and deorbit
  - Cover and thermally protect SSME #1 opening
- Payload carrier (expendable)
  - New shroud/Strongback
  - Skin/stringer/ringframe construction
  - 15′D x 72′L usable payload space
  - Sprayable low temperature ablator
  - Internal acoustic/thermal insulation
- Avionics
  - Uses mature design components from STS and other applications
  - Requires some new integration and software

Fig. 4.9—Shuttle-C sidemount configuration

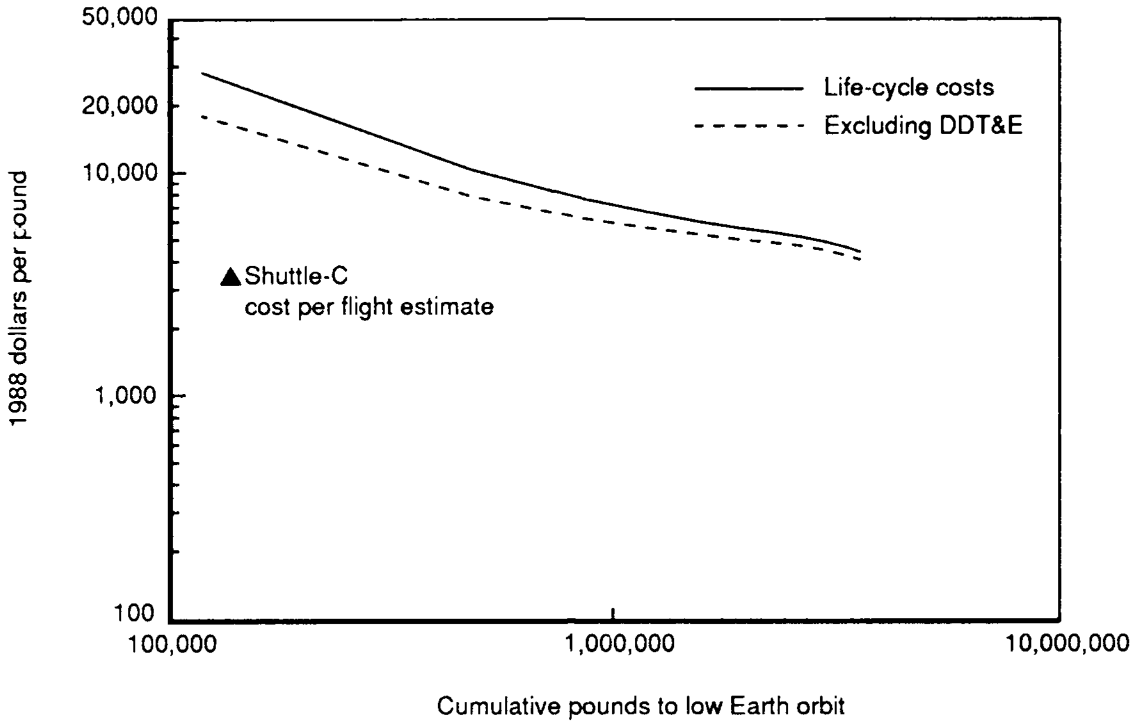


Fig. 4.10—Launch costs—Shuttle-C

Table 4.5

ESTIMATED SHUTTLE-C PRODUCTION COSTS

Boattail/aft thrust structure	$120 million
Cargo carrier	$ 85 million
Avionics	$ 75 million
3 shuttle main engines	
(@$40M each)	$120 million
Total	$400 million

Table 4.6

ESTIMATED SHUTTLE-C O&S COSTS

External tank	$ 20 million
Solid rocket boosters	
(@$20M each)	$ 40 million
Launch operations	$ 30 million
Flight operations	$ 30 million
Total	$120 million

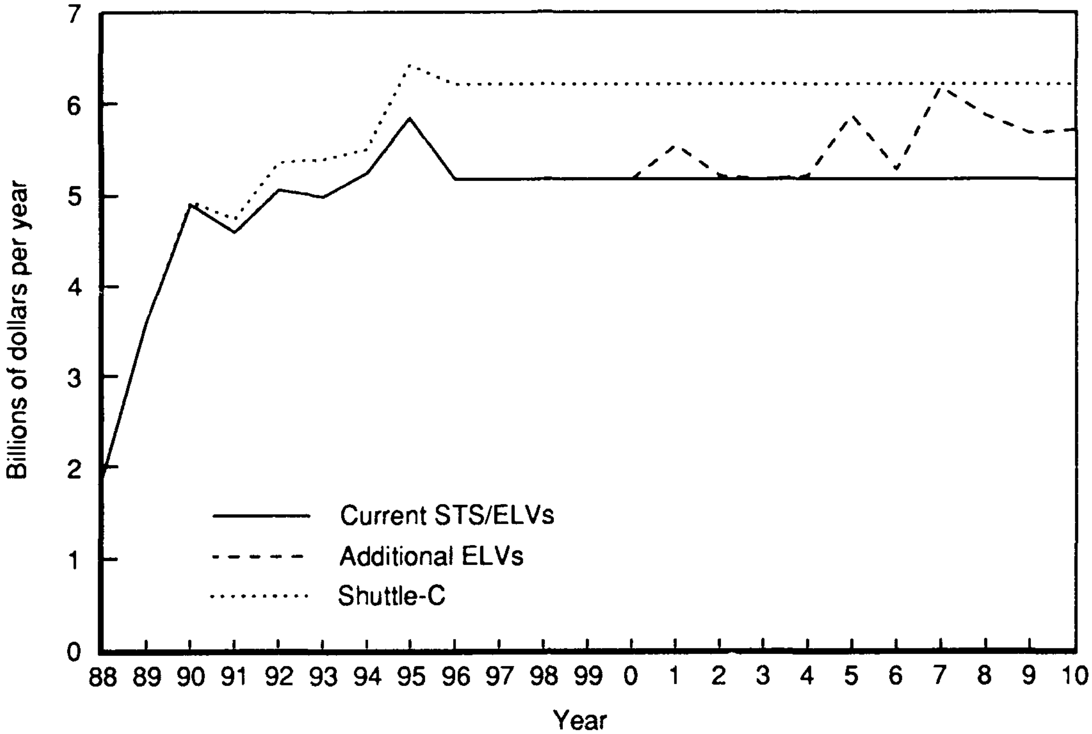


Fig. 4.11—Nominal demand/launch vehicle options

4.3.3 Launch Vehicles for an Expanded Civil Demand

In the case of an expanded civil demand, the level of space traffic increases significantly. Payload capacity requirements would grow from the current 20 to 24 STS equivalent flights per year to 50 to 55 flights per year. This level of effort would require new vehicles as buying additional STS and ELV flights would greatly exceed current production and launch complex rate limits. The United States could certainly increase production and launch capacities for existing launch vehicles, but this is not as effective as adding new vehicles for high demand levels.[9]

Figure 4.12 shows the addition of a heavy-lift vehicle from the ALS program to a baseline of STS and ELV flights (as defined in Table 4.4). This ALS HLV does not fly at its maximum rate, but rather at a lower level that matches the growth in the expanded civil demand baseline. An overview of the planned ALS development path is shown in Fig. 4.13.[10] The ALS HLV is assumed to begin flying in 1998 with one flight and grow steadily to 10 flights in 2010. Its upweight capacity of approximately 150,000 lb to LEO gives it a value of about 3.5 STS equivalents. The addition of a single additional ALS HLV flight is thus a significant increase in yearly upweight capacity.

A variant on the ALS HLV addition would be a transition plan that included both a Shuttle-C and an ALS HLV, meeting needs for heavy-lift (as with the space station) with a

[9]For a more extensive discussion of the tradeoff between improving existing vehicles or starting a new development, see Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28, U.S. Government Printing Office, Washington, D.C., September 1988.

[10]The ALS program includes not only a heavy-lift vehicle but smaller ones as well in a "family of vehicles" concept. Major Dale Carter, *Briefing on the Advanced Launch System*, USAF Space Division/ALQL, presented at The RAND Corporation, August 5, 1988.

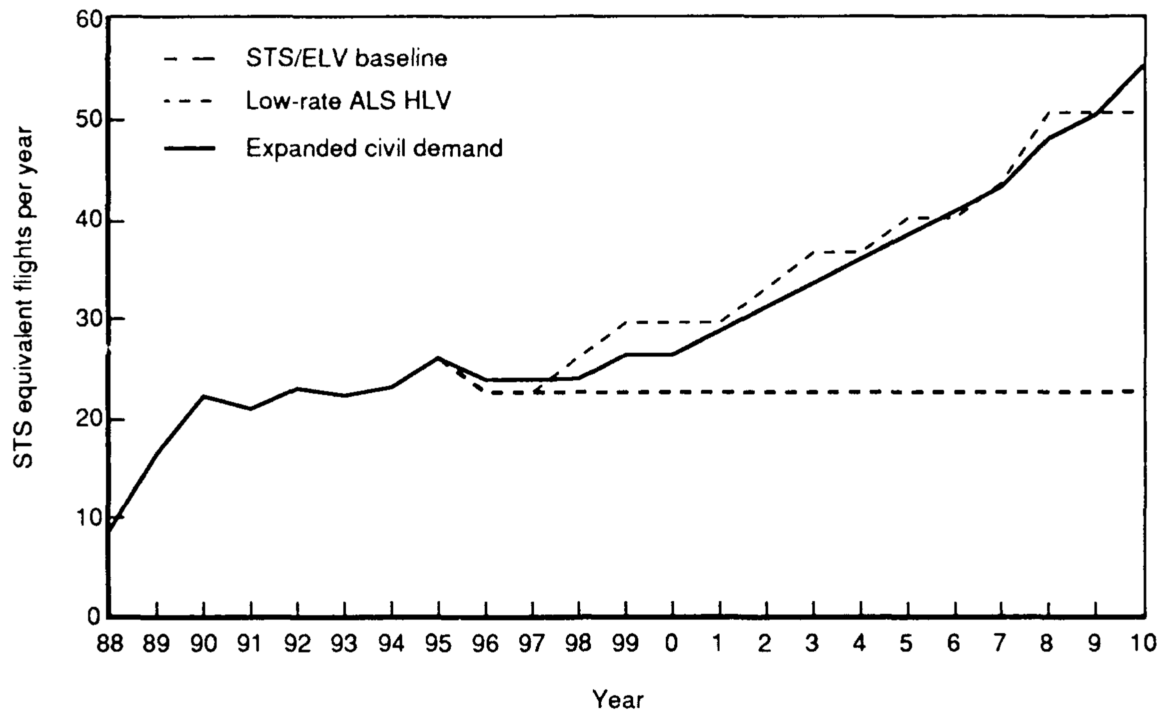
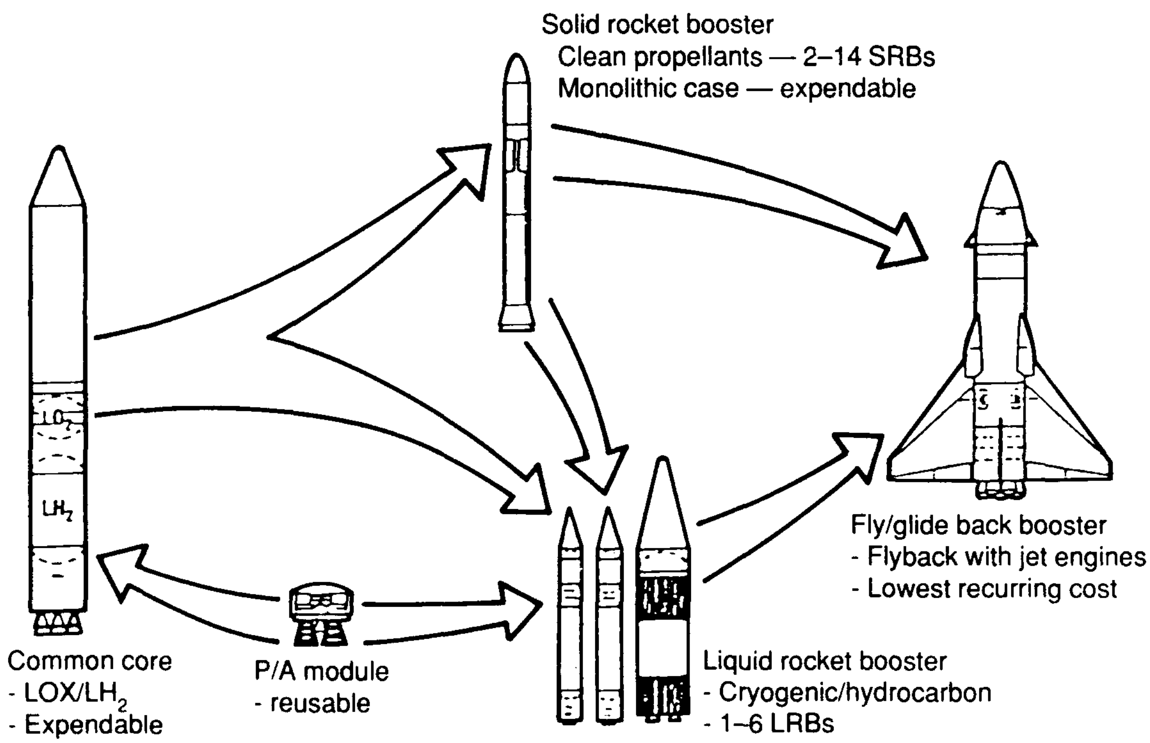


Fig. 4.12—Expanded civil demand/STS/ELVs and low rate ALS HLV



SOURCE: NASA and U.S. Air Force Systems Command.

Fig. 4.13—Advanced launch system (ALS) vehicle

vehicle that could be developed relatively rapidly. In later years, as payload traffic grows, an ALS HLV with lower recurring costs could be phased in after a longer development program, spreading development costs out over a longer period as well. Figure 4.14 shows what this transition plan would look like if built on a base of STS and ELV flights. Under this plan, the Shuttle-C makes its first flight in 1997, flies no more than three times per year, and is deactivated in 2007. The ALS HLV first flight does not occur until 2003 and builds up to 10 flights per year by 2010.

The major ALS HLV cost is from the development program in the mid-1990s. The program is assumed to be successful in lowering the cost per pound to orbit and thus the production and O&S costs for the ALS are relatively small in the out-years. ALS cost assumptions are shown in Table 4.7.

Figure 4.15 shows how the launch cost per pound drops as a function of the cumulative amount of mass placed in orbit. Later, in a summary of launch vehicle characteristics, the ALS cost per pound is listed as about $1000 per pound. This could occur with the launch of 10 million or more pounds into orbit. However, the ALS cost estimate involves a variety of fixed and variable factors which depend on desired flight rates and thus a single cost per flight number can be misleading. Nonetheless, the ALS may result in significant cost reductions over current launch vehicles.

Figure 4.16 summarizes the costs of launch vehicle mixes applicable to the expanded civil demand baseline. As in the summaries for earlier demand projections, payload costs have been removed to more clearly show differences in launch vehicle costs. A constant

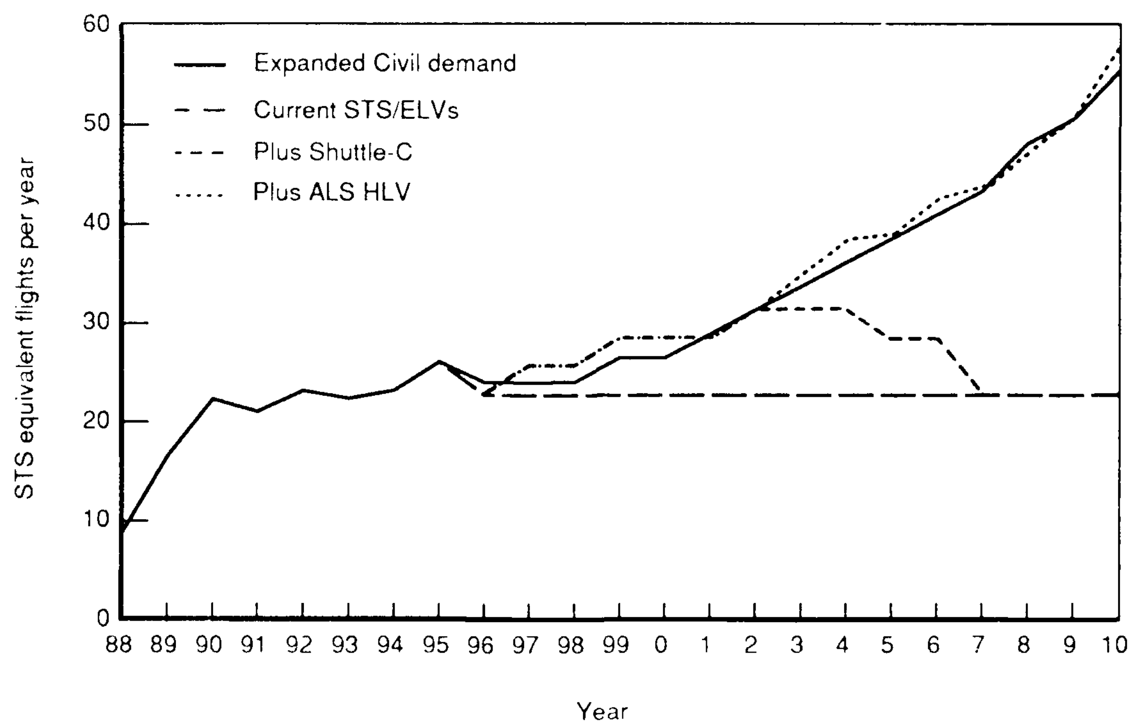


Fig. 4.14—Transition plan with Shuttle-C and ALS HLV, expanded civil demand

Table 4.7

ESTIMATED ALS COSTS[a]

DDT&E	$9.5 billion (spread over six years, ending before first launch)
Facilities costs	$150 million per peak flight rate (spread over four years, ending before capability is required)
Production costs	$1.7 billion (reusable elements built over five years)
Operations costs	$241 million per year (independent of flight rate)
Operations costs per launch	$33 million per flight (including expendable elements)

[a]These cost estimates are from the Office of Technology Assessment (OTA), *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383, U.S. Government Printing Office, Washington, D.C., July 1988.

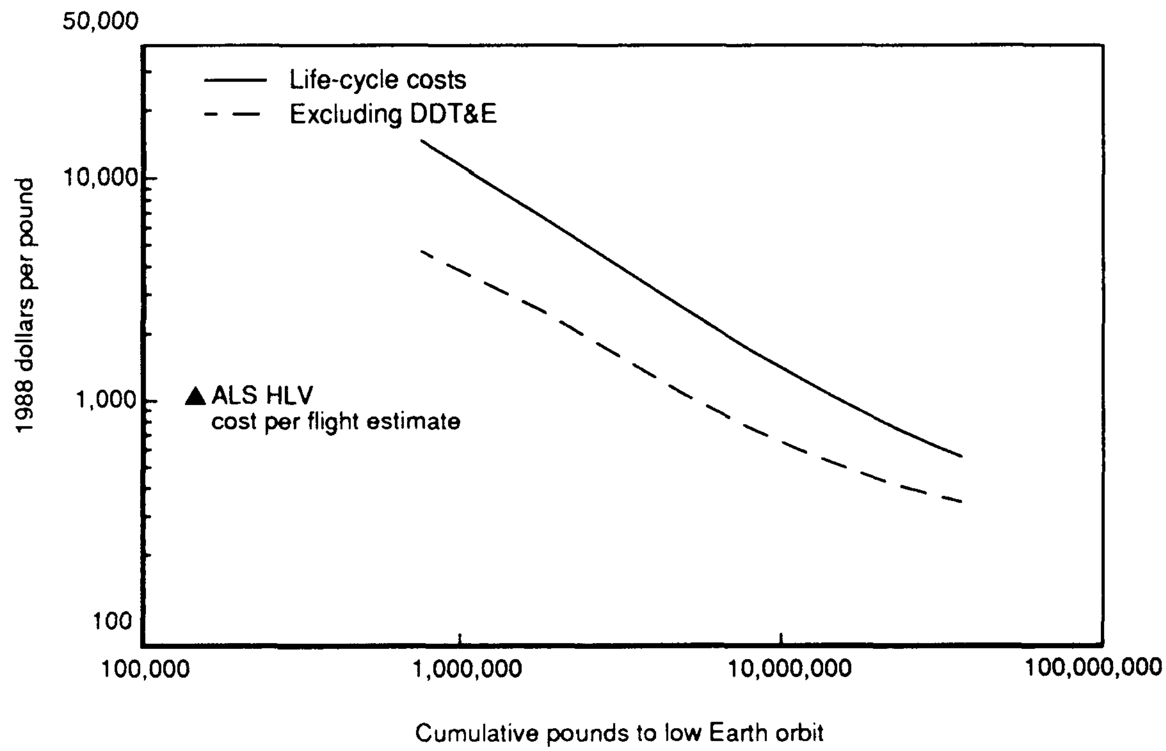


Fig. 4.15—Launch costs for the ALS

baseline of STS and ELV flights was assumed when either an ALS HLV or mix of ALS HLV and Shuttle-C was added to that base. Both additions carry high upfront costs due to ALS development costs. Both mixes meet the expanded civil demand flight rate, but the use of a Shuttle-C delays the peak development costs of the ALS for several years. In contrast, the

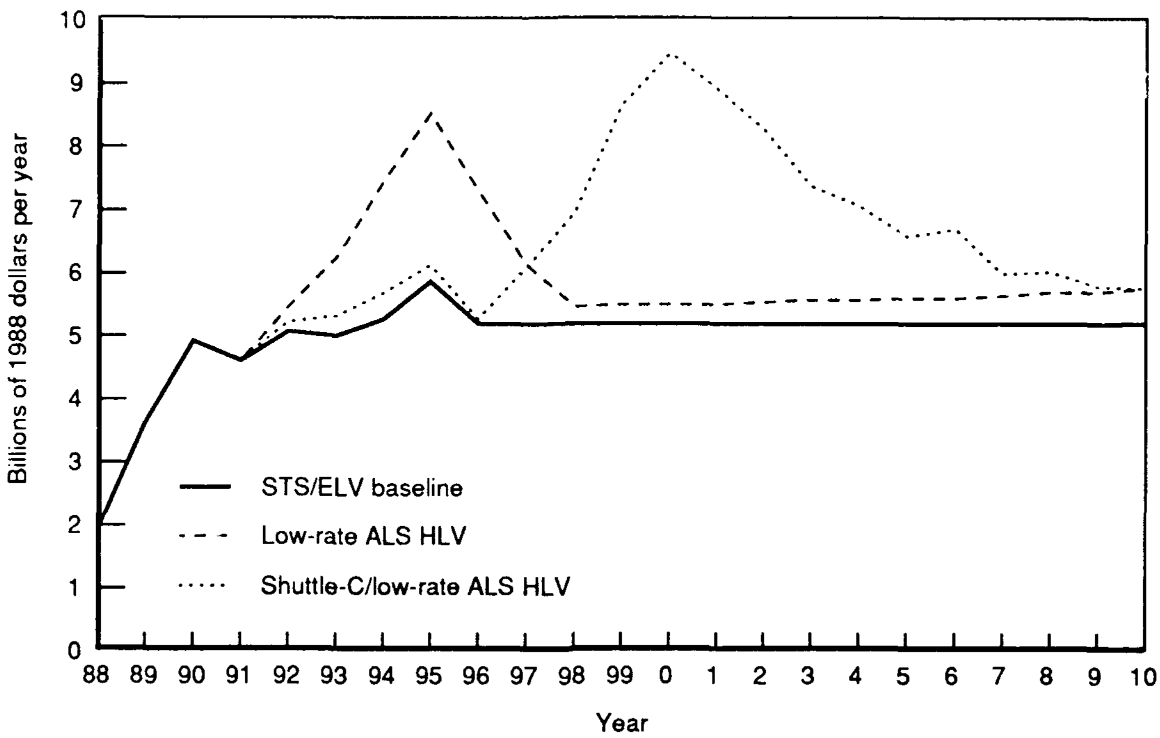


Fig. 4.16—Expanded civil demand/launch vehicle options

ALS-only option incurs costs sooner but is able to more quickly reduce operating costs to lower levels in the out-years. Development costs for the ALS are greater than the recurring cost of operations at this demand level. The Shuttle-C is the converse, with development being modest compared with recurring costs.

4.3.4 Launch Vehicles for an Expanded DoD Demand

The most stressing projection is the expanded DoD demand baseline, which represents a full deployment of SDI systems within the next 20 years as well as continuing nominal civil efforts. It represents an increase over previous peak efforts by about a factor of five and sustained for many more years. It is widely recognized that current launch vehicles would be inadequate to this task and new systems would need to be developed. Being able to support a future decision to deploy SDI systems is in fact one (but not the only) reason for examining development of the ALS family of vehicles.

Figure 4.17 shows both the expanded civil and expanded DoD demand levels. STS and ELV flights are still maintained to fly normal scientific, civil, and military payloads. The ALS HLV is developed to meet the expanded DoD demand level. The ALS HLV's yearly flight rate is closely matched with the growing DoD demand. In this figure, it is difficult to see the difference between the ALS HLV capability line and the expanded DoD demand level. The expanded civil baseline demand is shown for perspective.

Based on experience with an expanded civil demand, Shuttle-C flights are introduced to support the expanded DoD demand. The effect is shown in Fig. 4.18. The overall contribution is rather small, due to the limited flight rate of the Shuttle-C compared to the ALS HLV

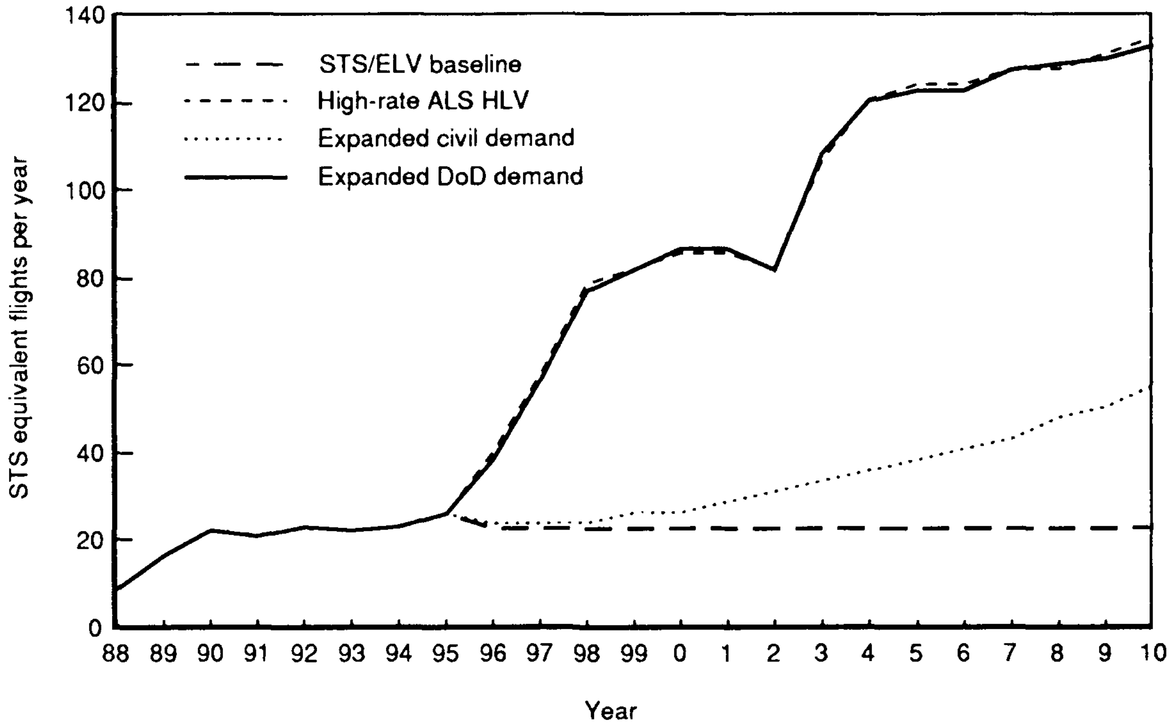


Fig. 4.17—Expanded DoD demand/STS/ELVs and high rate ALS HLV

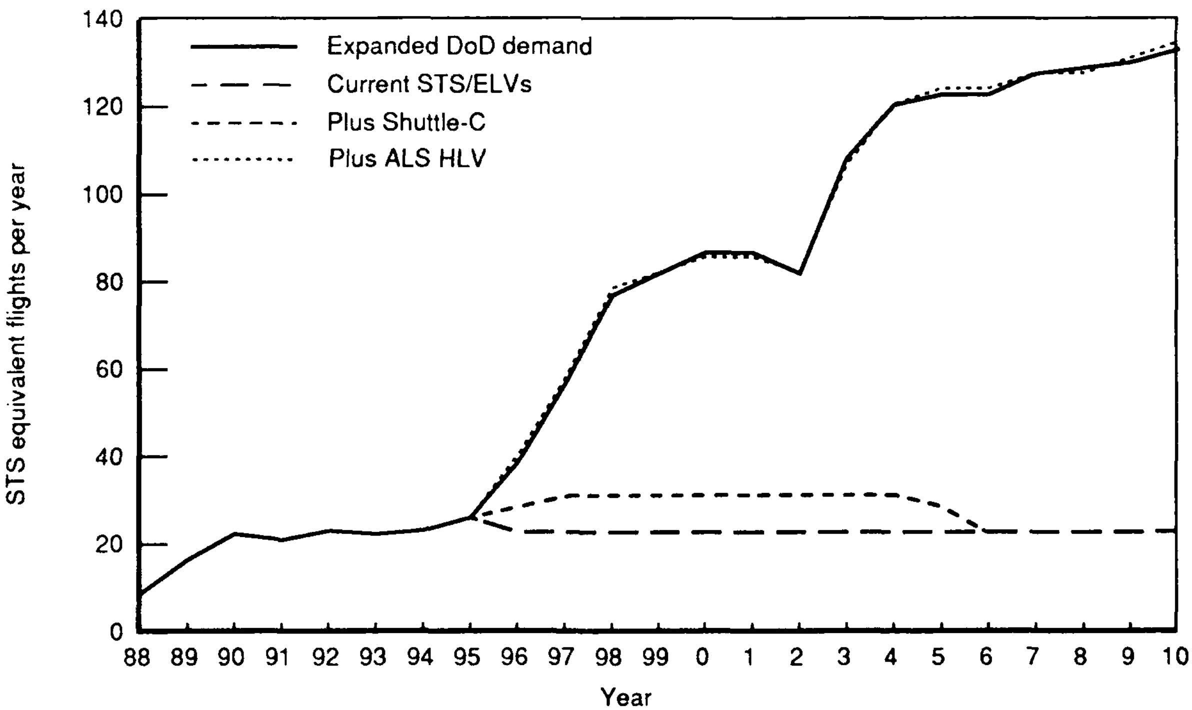


Fig. 4.18—Transition plan with Shuttle-C and ALS HLV, expanded DoD demand

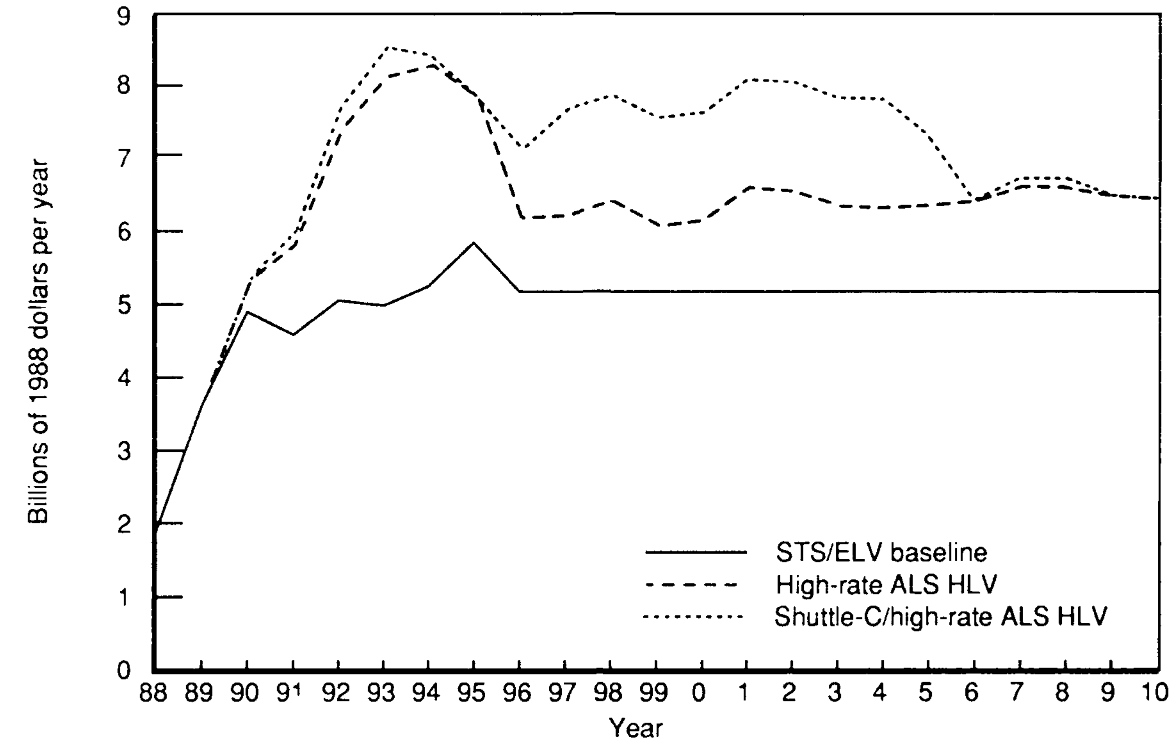


Fig. 4.19—Expanded DoD demand/launch vehicle options

and its smaller capacity per flight. The Shuttle-C was again assumed to operate only for 10 years in support of the space station and the initial build-up of ALS flights.

Figure 4.19 summarizes the two expanded DoD demand options after excluding common payload costs. The baseline of STS and ELV flights dominates the launch costs if allowed to continue. The entire ALS effort would be needed, however, to support the SDI deployment and thus would not be an option for off-loading current vehicles.[11] As might be expected, the combination of both a Shuttle-C and ALS is more costly than an ALS alone.
The ALS dominates upfront development costs but is assumed to lower operations costs afterwards. Its operating costs are small even compared with STS/ELV costs. Shuttle-C development costs are barely visible at this scale, but its lower flight rate costs about as much as the higher capacity, higher flight rate of the ALS HLV. The economic tradeoff of development versus operations costs will be covered briefly in the next section.

4.4 COSTS OF ALTERNATIVE LAUNCH VEHICLE MIXES

Recurring and nonrecurring costs were combined to estimate the total cost of a launch vehicle mix for a given demand. Average recurring costs per flight were assumed constant for all vehicles in the 1988–2010 period. New vehicles, such as the ALS HLV and Shuttle-C, included nonrecurring costs for the estimated flight rates. Production rate effects, such as

[11] If the ALS program is able to lower the cost of access to space at acceptable levels of reliability, ELVs may be phased out in preference to using ALS vehicles. Even the shuttle could conceivably be replaced by a man-rated ALS using a crew capsule. How the commercial ELV industry and NASA would react to such options is a moot question, as are questions of whether the Department of Defense will be able to procure ALS capacity in excess of military requirements.

learning curves, were not significant given the larger uncertainties of the baseline cost estimates.

Given that, in aggregate, payload costs are larger than launch costs, total costs for vehicles and payloads will increase as demand rises. This is shown in Fig. 4.20 where launch vehicle options are grouped together for the four baseline demands. The numbers under each bar signify the launch vehicle mix listed in Table 4.8.

Different costs of launch vehicles are all dominated by the common costs of payloads for each baseline demand. Total costs of launch vehicles and payloads range from a low of about $200 billion between 1988 and 2010 to a high of $900 billion. The 1988 manifest alone can be expected to cost over $100 billion between 1988 and 1995.

If a discount rate is applied to these costs, nearer term costs are weighed more heavily than later costs. Reducing total costs spread over time to a common "present value" is thus a useful way of comparing options where expenses occur at different times. Figure 4.21 shows the result of applying a modest 5 percent per year discount rate. The most obvious result is a compression of the range of total costs. The expanded DoD demand total cost still stands out as larger than all the rest, even discounting the costs in the out-years.

As might be expected, near-term costs from the 1988–1995 manifest make up a large portion of the total cost figures (i.e., compare the height of Option 0 to the heights of Options 1-8). Since payload costs are the same for each option, total cost differences are due to the launch vehicle mixes and the differing levels of payload demand. For a given level of demand, total cost differences result only from launch vehicle mix differences. Under the nominal demand and the expanded DoD demand levels, Options 6 and 10 are the most expensive. These options both include the Shuttle-C.

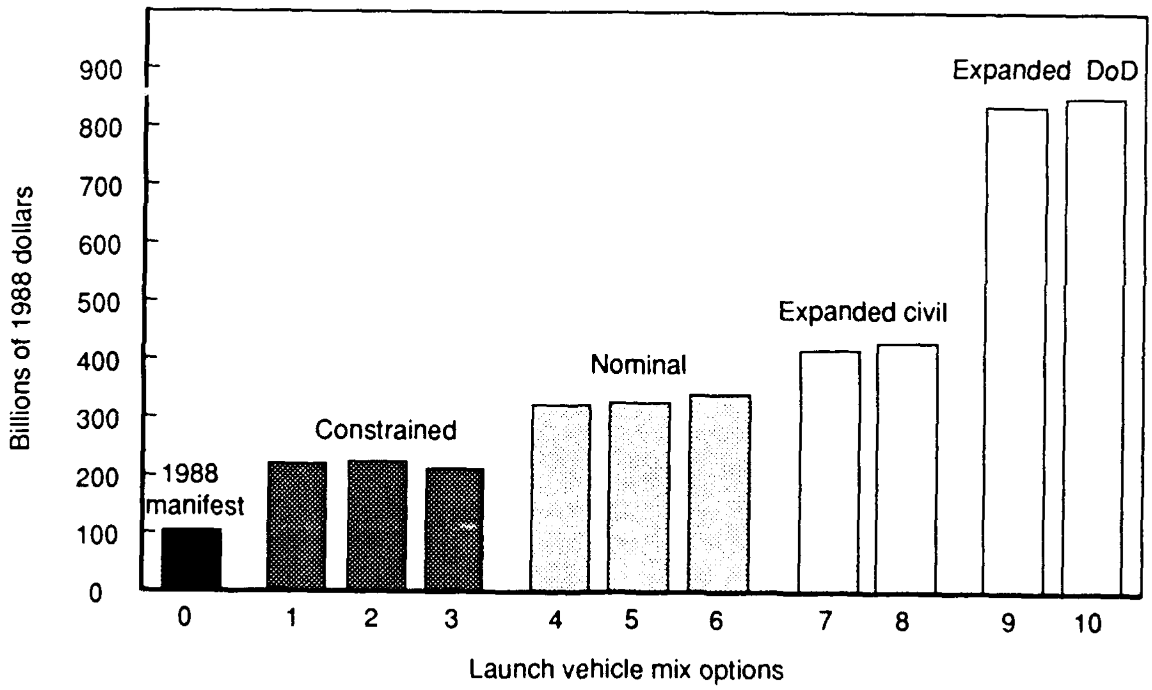


Fig. 4.20—Total costs undiscounted for all options (launch vehicles and payloads), 1988–2010

Table 4.8

LAUNCH VEHICLE MIXES AND OPTION NUMBERS

Option Number	Demand Level	Launch Vehicle Mix
0	1988 Manifest	1988–95 NASA/DoD manifest
1	Constrained	Reduced STS/ELV rates
2	Constrained	STS only after 1995
3	Constrained	ELVs only after 1995
4	Nominal	Current STS/ELV rates
5	Nominal	Plus more ELVs
6	Nominal	Or add Shuttle-C flights
7	Expanded civil	Low flight rate ALS HLV
8	Expanded civil	ALS HLV plus Shuttle-C
9	Expanded DoD	High flight rate ALS HLV
10	Expanded DoD	ALS HLV plus Shuttle-C

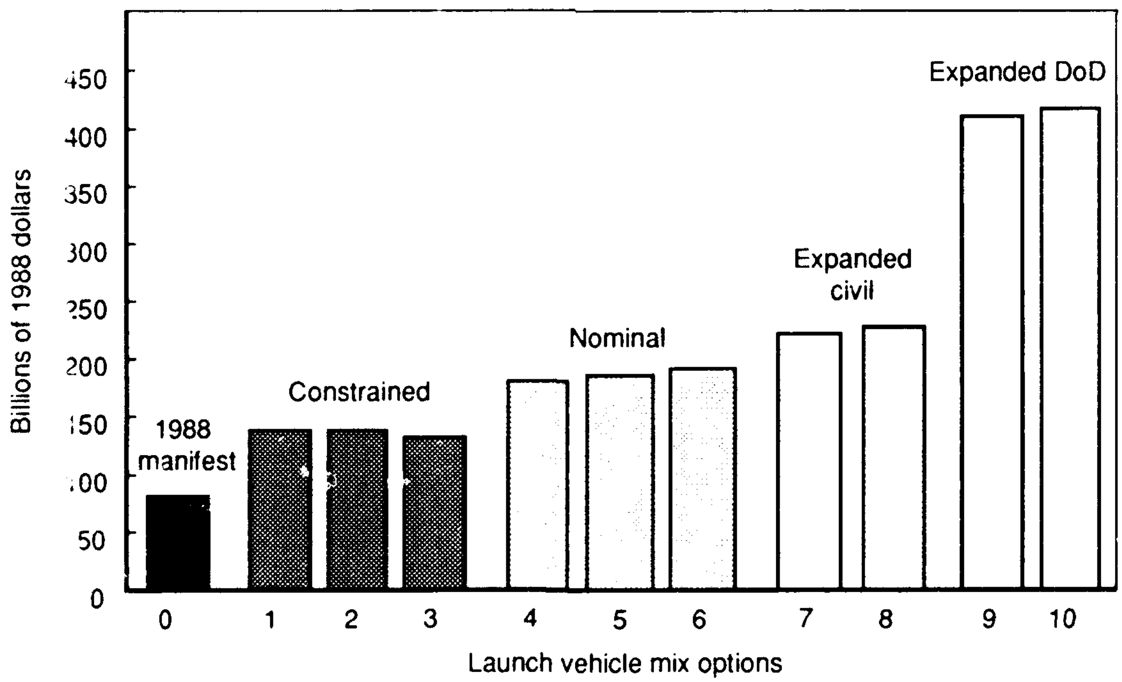


Fig. 4.21—Total costs at 5 percent discount rate for all options (launch vehicles and payloads), 1989–2010

Undiscounted total launch vehicle costs are shown in Fig. 4.22. The cost differences among launch vehicle mixes are clearer without the dominance of payload costs. As expected, launch vehicle costs rise as flight rates rise. For each demand level, launch vehicle mixes can be ranked by total costs, as shown in Table 4.9. The cost of vehicles for the 1988 manifest are already included in each mix.

Near-term launch costs through 1995 (Option 0) make up a large proportion of total launch vehicle costs. Even with a 5 percent discount rate there is no change in the rank orders, as shown in Fig. 4.23. The main impact of a discount rate is to compress the options closer together and lower the range of present value costs. Undiscounted launch vehicle costs extend from $70 billion to $159 billion. At a 5 percent discount rate, the range is reduced to $44 to $90 billion (with the 1988–1995 period accounting for $28 billion).

After comparing total costs and launch vehicle mix costs, the affordability of the options is the next obvious question. While it is difficult, if not impossible, to predict the future size and composition of the federal budget, the growth required to implement any of the launch vehicle mixes and payload demands listed above can be estimated. Taking 1989 as the first "normal" year after the loss of the Challenger, the compound annual growth required to reach 2010 cost levels can be derived.

Figure 4.24 illustrates that the budget for launch vehicles and payloads may either hold constant or decline from 0 to 1 percent per year for the constrained case or increase at a rate of almost 9 percent per year for the expanded DoD demand case. Table 4.10 expresses Figure 4.24 in specific numbers for each demand level.

Payload costs would dominate most of these growth rates, assuming that new launch vehicles do not lower the cost of payload design and construction significantly. Another point to keep in mind is that the long-term growth rate for the U.S. economy is about 2.4 percent per year for the post-World War II period.[12] The constrained demand budget represents a decline in U.S. space effort from current levels. The nominal demand budget would keep U.S. effort at approximately the same level for the future, whereas both expanded demand cases represent increased U.S. effort in space.

In the case of launch vehicle costs alone, the growth rates are smaller but the differences are more pronounced. Figure 4.25 shows the budget growth rates for various launch vehicle options. The option numbers are those listed in Table 4.8. The use of all ELVs after 1995 in the constrained demand case (Option 3) would cause the largest drop in the launch vehicle budget, averaging almost 1.5 percent per year through 2010. The largest drop for any one year would occur in the late 1990s with the cancellation of shuttle-related activities and no new start on a replacement manned vehicle.

As with total costs, launch vehicle costs for the nominal demand grow about 1.7 to 2.6 percent per year. The expanded civil demand options both reach the same level, but with growth occurring at different times. Overall, an average rate of 2.2 percent per year would be required. This is surprisingly less than the nominal case, which uses the Shuttle-C at reduced flight rates through 2010. Finally, the expanded DoD demand requires an average growth of 2.8 percent per year. This seems modest given the great increases in launch capacity, but it assumes high upfront development costs are balanced against lower operating costs at high flight rates.

The importance of budgetary constraints to payload and launch costs is shown in Fig. 4.26. To simplify comparisons, assume payload and launch costs of $35,000 and $3000 per pound, respectively. At a combined cost of $38,000 per pound, the entire U.S. space budget (civil and military) is required to place a little over 500,000 pounds per year in orbit. The entire U.S. Air Force budget could place 2.5 million pounds per year in orbit, which is less than the level of an expanded DoD demand. If payload and launch costs can be reduced to

[12]Executive Office of the President, *Historical Tables—Budget of the United States Government, FY 1989*, Office of Management and Budget, U.S. Government Printing Office, Washington, D.C., 1988.

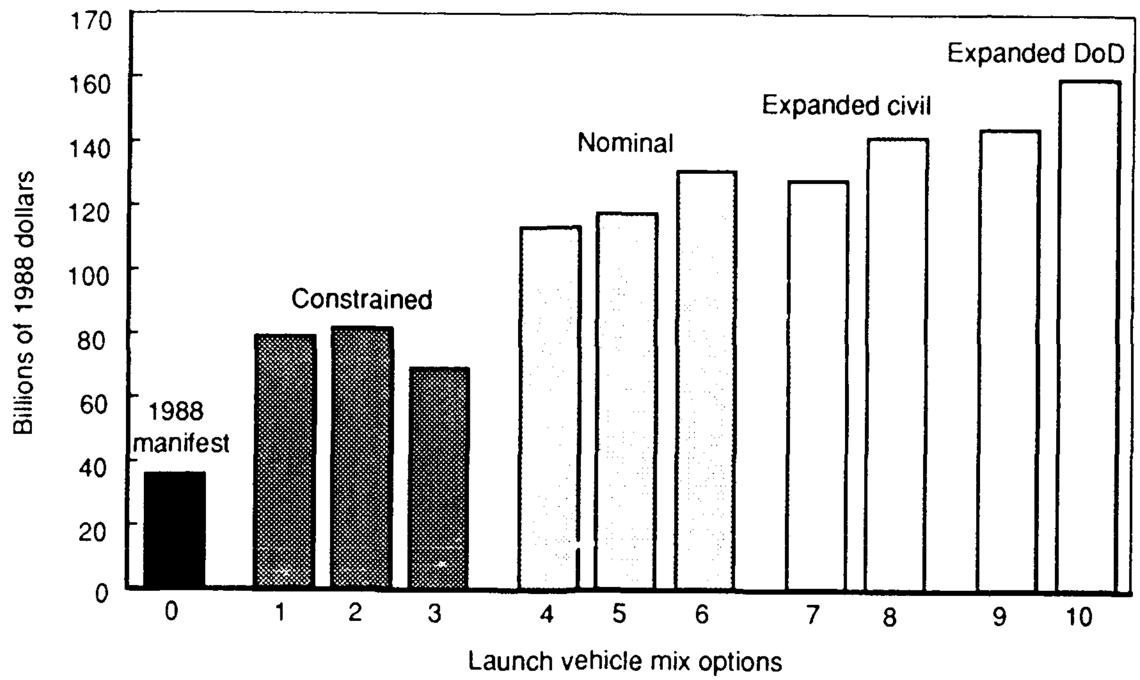


Fig. 4.22—Launch vehicle costs undiscounted for all options, 1988–2010

Table 4.9

LAUNCH VEHICLE MIXES RANKED BY COST, 1988–2010

Mix	Cost ($1988)	Average $/lb
Manifest 1988–1995	$36 billion	$5300
Constrained demand		
ELVs only after 1995	$70 billion	$4900
STS/ELVs	$79 billion	$5500
STS only after 1995	$82 billion	$5700
Nominal demand		
Current STS/ELVs	$114 billion	$5400
Plus more ELVs	$118 billion	$5600
Or add Shuttle-C	$131 billion	$6300
Expanded civil demand		
Low flight rate ALS HLV	$128 billion	$4400
ALS HLV and Shuttle-C	$142 billion	$4900
Expanded DoD demand		
High flight rate ALS HLV	$144 billion	$2100
ALS HLV and Shuttle-C	$159 billion	$2300

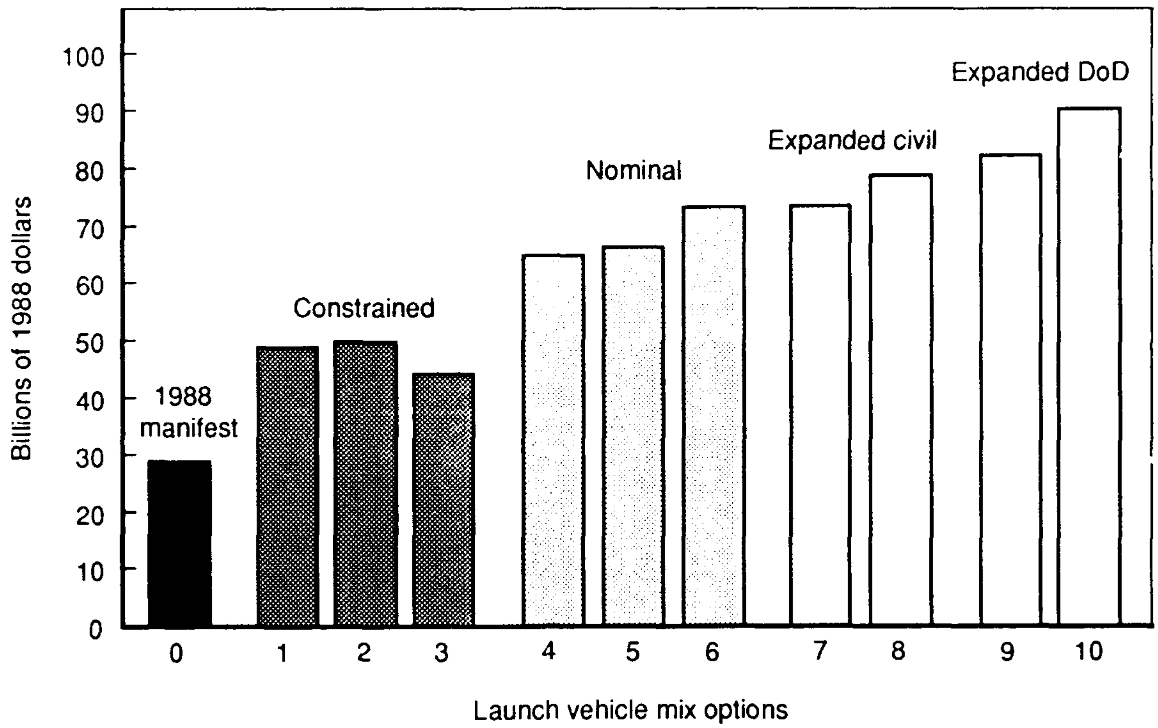


Fig. 4.23—Launch vehicle costs at 5 percent discount rate for all options, 1988–2010

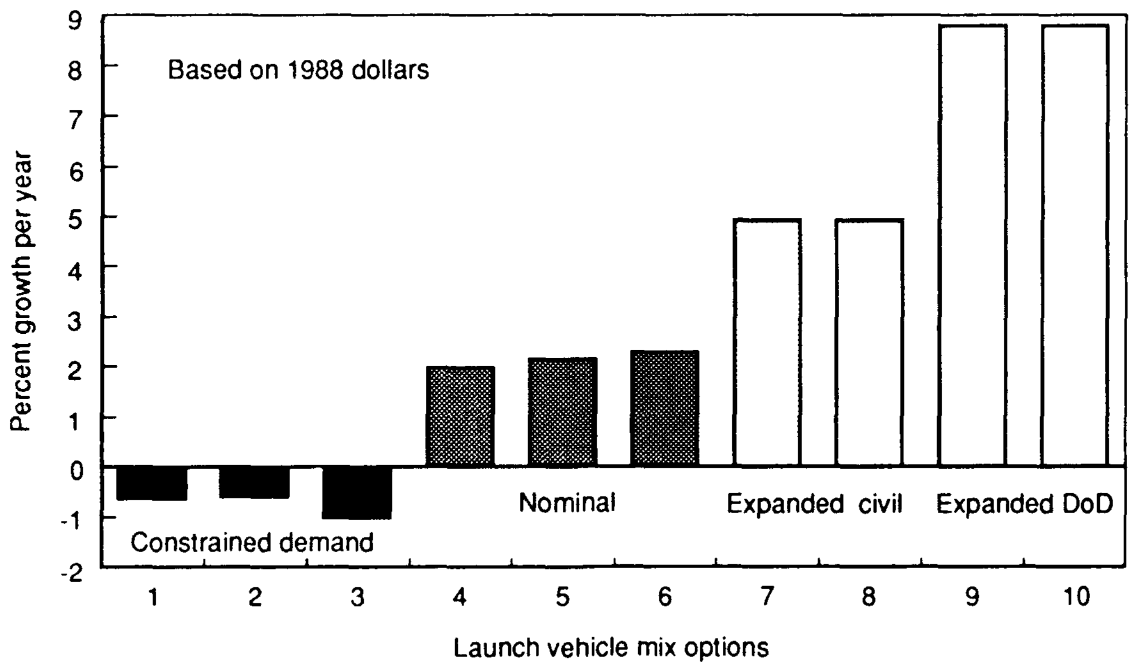


Fig. 4.24—Growth rates for launch and payload costs, 1989–2010

Table 4.10
BUDGET GROWTH RATES FOR LAUNCH VEHICLES AND PAYLOADS, 1989–2010

Constrained demand	–0.6 to 1.0% per year
Nominal demand	2.0 to 2.3% per year
Expanded civil demand	about 5% per year
Expanded DoD demand	about 8.8% per year

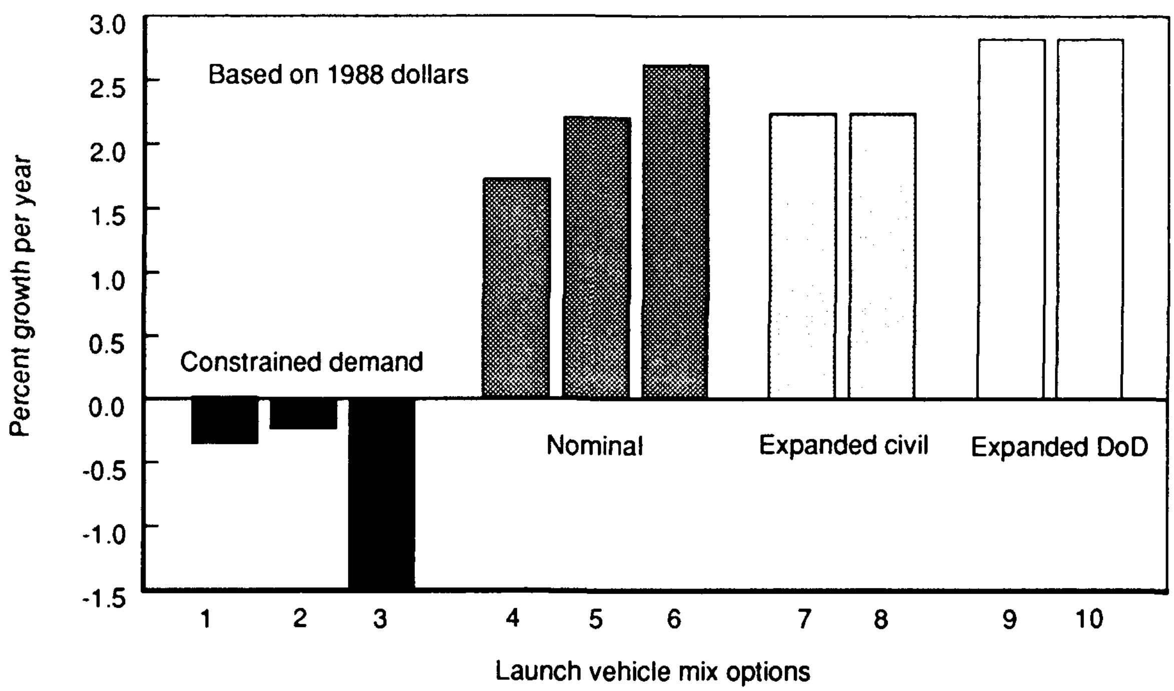


Fig. 4.25—Growth rates in launch costs, 1989–2010

$10,000 and $300 per pound, respectively, the United States could afford greater levels of space traffic. The current U.S. space budget could support the expanded civil demand level and the expanded DoD demand would at least cost less than the Air Force budget.

4.5 RISKS DUE TO VEHICLE UNRELIABILITY AND STANDDOWN DELAYS

Launch capacity and direct costs are not the only considerations in choosing a launch vehicle mix. As the Challenger loss and subsequent standdown showed, vehicle reliability and the ability to recover rapidly are also valuable qualities. This subsection estimates

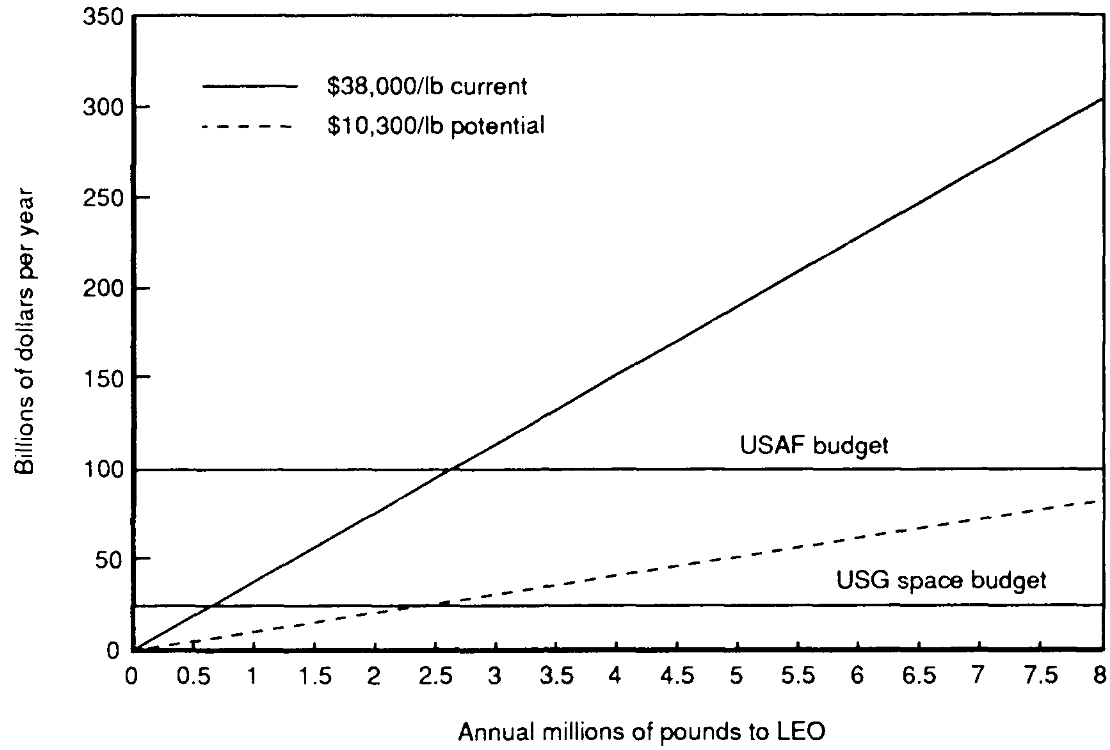


Fig. 4.26—Total launch and payload costs and budgets

the amount of payload losses and delays that can be expected from the launch vehicle mixes described above.

For each launch vehicle an average reliability figure was assigned.[13] The yearly "risk exposure" is calculated by multiplying each vehicle's probability of failure by its number of flights per year and its STS equivalent size, and then summing the expected losses for all vehicles in a specific vehicle mix option (see Eq. (4.1)). The total risk exposure is then the sum of the expected payload losses from all flights for 1988 through 2010 (see Eq. (4.2)) in units of "STS equivalent payloads." Vehicle reliabilities are assumed to be independent, so that a standdown of one does not cause a standdown of another.

Risk exposure per year = Sum over all launch vehicles of
(Probability of failure) (STS equivalent payload) (No. of launches) (4.1)

Total risk exposure = Sum over Eq. (4.1) for 1988–2010 (4.2)

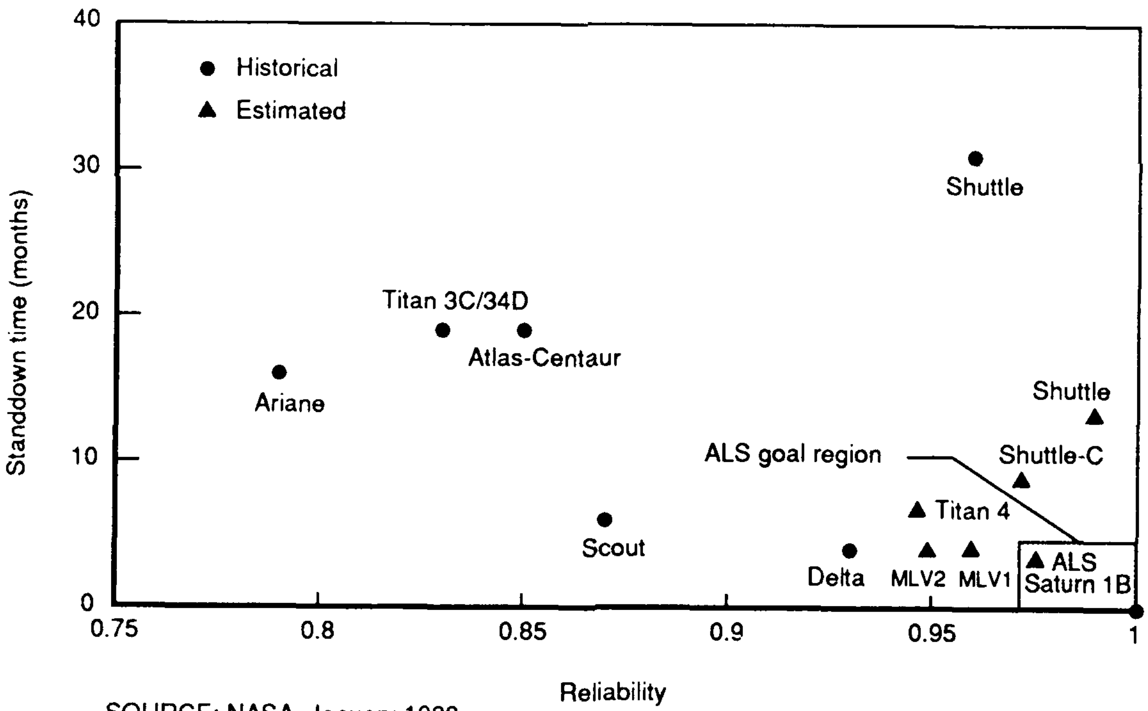
Table 4.11 lists the reliabilities, standdown time given failure, and STS equivalent values for the launch vehicles considered. The reliability and standdown delay estimates are for future performance (not historical), and thus are goals to be achieved. Figure 4.27 shows how these estimates compare with historical results. The historical reliabilities include the

[13]These estimates are covered in App. D and Office of Technology Assessment, op. cit. STS reliability prior to STS-26 was only 96 percent. A reliability of 99 percent was considered to be an optimistic, but achievable level for post-Challenger shuttle flights. See National Research Council, *Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization*, National Academy Press, Washington, D.C., October 1986.

Table 4.11

ESTIMATED LAUNCH VEHICLE RELIABILITIES, STANDDOWN DELAYS, AND STS EQUIVALENT SIZES

Launch Vehicle	Reliability	STS Equivalent Size	Standdown Delay (months)
Shuttle	0.99	1	12
Delta	0.96	0.25	4
Atlas-Centaur	0.95	0.5	4
Titan 34D & 4	0.95	0.75	6
Titan 2	0.92	0.3	6
Atlas E/F	0.92	0.3	4
Shuttle-C	0.98	2.75	8
ALS HLV	0.98	3.5	3



SOURCE: NASA, January 1988

Fig. 4.27—Standdown time vs. vehicle reliability

early failures for each vehicle. The future performance of proven vehicles is assumed to be better. The historical standdown figures are for the latest occurrence, as of January 1988, and are not averages. Again, future performance should be better. It is difficult to say whether a truly new vehicle such as the ALS will do significantly better, but it was assumed that the program would attain its reliability and standdown goals.

After estimating expected payload losses, expected standdown delays are calculated. Probabilities of failure are multiplied by the number of launches per year and average standdown time for each vehicle; this is further multiplied by the STS equivalent size of each launch vehicle. Standdown times, like risk exposure, are calculated for each year and then summed for all years. The units of measure for standdown delays are "STS equivalent months," that is, one STS-sized payload delayed for one month. No attempt was made to convert this delay into dollar units because of a lack of agreement over allocatable costs and the many individual circumstances with payload delays.[14]

Expected losses and delays were converted into percentages of total traffic demand. The percentages for payload losses due to vehicle failures are shown in Fig. 4.28. These are the losses expected for the 1996-2010 period, beyond the 1988 manifest. For 1988–1995, an average 3 percent loss rate was estimated. Losses for each demand level and applicabl launch vehicle mix are listed in Table 4.12.

For the constrained and nominal demand cases, the average losses increase as more ELVs are added to the inventory mix. The difference between the mixes could narrow, however, if shuttle reliabilities do not increase after its return to flight. For the expanded demand cases, the number and capacity of ALS HLVs dominates the Shuttle-C and thus little difference can be seen between mixes with both Shuttle-C and ALS HLV or the ALS HLV alone.

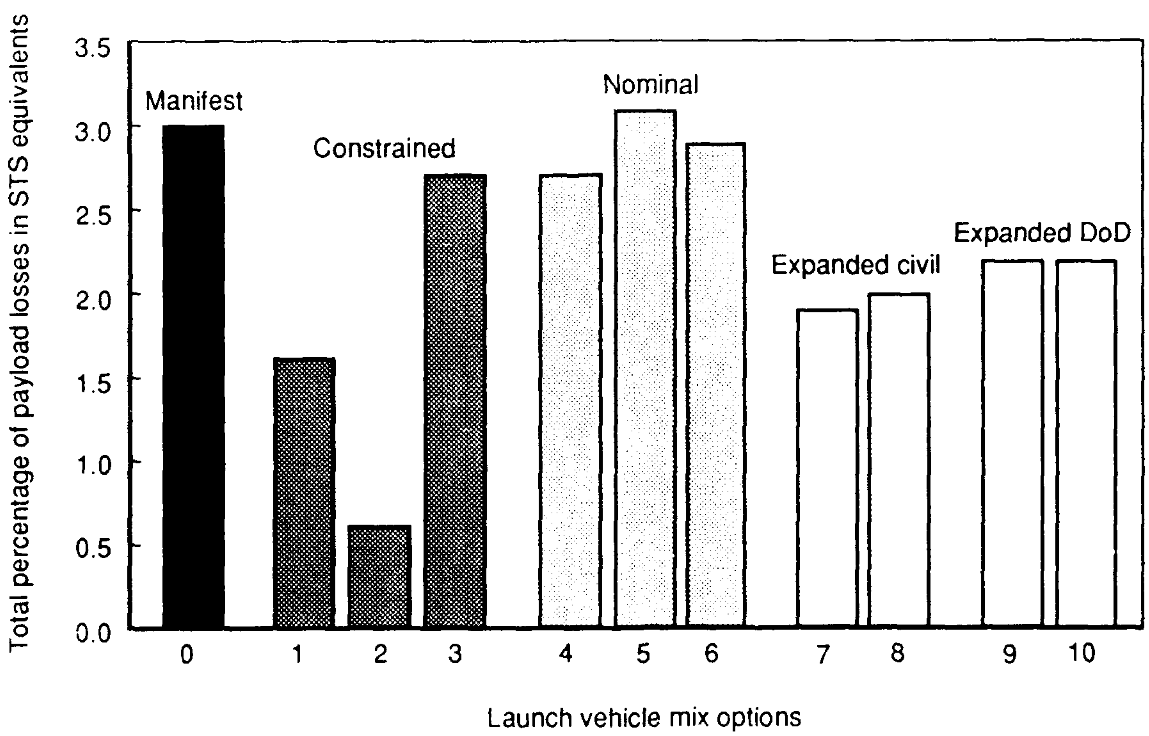


Fig. 4.28—Comparison of expected percent payload losses across demand levels

[14]In addition to storage costs, most payloads have associated support teams that have to be kept together. Aside from direct costs, there are opportunity costs that are even more difficult to quantify, such as missed scientific observations and decreased national security.

In the case of an expanded civil demand level, expected losses are comparable in both choices of vehicle mixes. Flight rates higher than those found for nominal demand levels are sustained because of (the assumed) high reliabilities and short standdowns of ALS vehicles. The same is true for the case of expanded DoD demand. Although expected absolute losses are larger than those for expanded civil demand, the reliability and standdown goals for ALS are still assumed to be met. The losses at the high end are not trivial, amounting to about 40 shuttle payloads. In comparison, losses of five shuttle payload equivalents can be expected between 1988 and 1995 on the 1988 manifest.

The situation for standdown delays is similar to that of payload losses above. Figure 4.29 is an overview of payload delays as a percent of total payloads flown. For 1988–1995, the estimated delay rate due to vehicle failures and standdowns is 0.07 percent. Estimates of other delay percentages are shown in Table 4.13.

As more ELVs are added, the number of expected delays increases. Delays at the high demand levels amount to about 170 STS equivalent months, similar to the 32 month standdown of the shuttle fleet.[15] In comparison, delays of over 30 STS equivalent months can be expected between 1988 and 1995. Assuming a high reliability, short standdown ALS means that delays can be kept to current levels while sustaining greatly increased traffic rates to orbit. If such goals are not met, delays, like losses, will increase in direct proportion to the expanded traffic levels.

Table 4.12

ESTIMATES OF EXPECTED PAYLOAD LOSSES FOR 1996–2010

Option No.	Demand Level	Average Percent Loss (STS Equivalents)
	Constrained	
2	STS only after 1995	0.6
1	STS/ELVs	1.6
3	ELVs only after 1995	2.7
	Nominal	
4	Current STS/ELVs	2.7
6	Plus Shuttle-C	2.9
5	Or add more ELVs	3.1
	Expanded civil	
7	Low flight rate ALS HLV	1.9
8	ALS HLV and Shuttle-C	2.0
	Expanded DoD	
9	High flight rate ALS HLV	2.2
10	ALS HLV and Shuttle-C	2.2

[15]The standdown delay resulting from Challenger's loss was estimated as 164 STS equivalent months: 32 months times a four shuttle orbiter fleet plus the 36 months from the resumption of flights in September 1988 to the delivery of the replacement orbiter in October 1991.

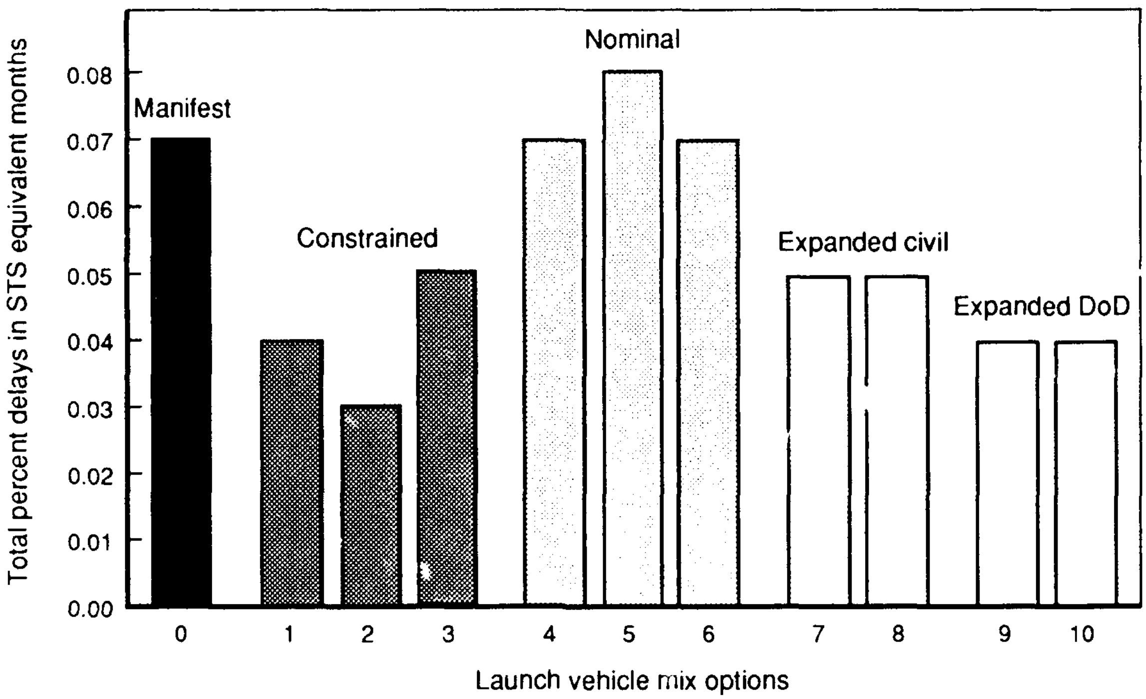


Fig. 4.29—Comparison of expected percent payload delays across demand levels

Table 4.13

ESTIMATES OF EXPECTED PAYLOAD DELAYS FOR 1996–2010

Option No.	Demand Level	Average Percent Loss (STS Equiv. Months)
	Constrained	
2	STS only after 1995	0.03
1	STS/ELVs	0.04
3	ELVs only after 1995	0.05
	Nominal	
4	Current STS/ELVs	0.07
6	Plus Shuttle-C	0.07
5	Or add more ELVs	0.08
	Expanded civil	
7	Low flight rate ALS HLV	0.05
8	ALS HLV and Shuttle-C	0.05
	Expanded DoD	
9	High flight rate ALS HLV	0.04
10	ALS HLV and Shuttle-C	0.04

V. INSTITUTIONAL CRITERIA FOR LAUNCH VEHICLE OPTIONS

5.1 EVALUATION CRITERIA FOR LAUNCH VEHICLE OPTIONS

The previous sections have reviewed a range of peacetime demand levels for U.S. government space traffic. The sections have also reviewed a range of launch vehicle options for meeting those demand levels, with attention paid to costs, performance, risks, and delays. The next question is how to combine information on potential alternatives with the need of decisionmakers to make evaluations and recommendations. This section first discusses evaluation criteria and then an evaluation methodology for ranking alternatives for implementation.

Discussions with members of industry, Congressional analysts and staff, OMB analysts, NASA officials, and Air Force officials as well as White House statements on national policy have highlighted three or four central issues that will be determining space transportation planning in the next decade and beyond.[1] The first issue is the concern over the federal deficit and the budgets available for civil and military space activities. Next are uncertainties over what national goals the United States should be pursuing in space—that is, the purposes for which space transportation is procured. Major national initiatives such as the Strategic Defense Initiative (SDI), a return to the Moon, or international cooperative missions to Mars can each have a profound affect on the required mix of launch vehicles, as shown earlier.

The most difficult issue is disagreement over the appropriate planning horizon for space transport. Some planners are concerned with meeting near-term needs such as the space station, whereas others are looking at long-term goals of space transportation such as increasing reliability and lowering costs, regardless of specific programs. Assumptions of future payload costs are but one example of how planning horizons affect launch vehicle choices. In the near term, payload costs will certainly dominate launch costs in total life-cycle cost estimates for space systems. In the far term, some analysts say this will continue, whereas others argue that future payloads will become cheaper as low-cost, reliable space transport becomes available. The interaction of launch costs and payload costs with overall traffic demand is just one of the uncertainties in implementing space transportation systems that are developed and operated over decades.

The issues noted above were separated into more specific evaluation categories for the alternative launch vehicle mixes. The general categories chosen were:

- Cost
- Performance
- Risk
- Policy

Obviously, decisionmakers would prefer the "best" launch vehicle mix, as characterized by low cost, high performance, low risk, and fulfillment of national policy objectives. How to actually measure these qualities is a more difficult problem. A greater level of detail is required in identifying specific evaluation criteria within each of the categories.[2]

Within the cost category, three evaluation criteria were selected. The first criterion is the total cost (recurring and nonrecurring) for the launch vehicle mix between 1990 and

[1]The identities of individuals interviewed are confidential except for their institutional affiliation.

[2]The evaluation criteria and their interpretation are the author's choices based on interviews and prior analyses. They will differ from the views of specific decisionmakers and their institutions.

2010, with the option of including the cost of the payloads expected for launch. The second criterion is the real budget growth required for the specific vehicle mix over the life of its operation. The third is the amount of peak funding required. Cost issues are discussed in Apps. B and D, and budget issues are treated in App. C.

Four evaluation criteria were selected within the performance category. The first is design adequacy—the ability of the launch vehicle mix to carry the payloads in the traffic demand. The second criterion is the overall reliability of the vehicles in the mix. Third is the resiliency of the mix, which is broader than reliability in that it measures the ability of the vehicle mix to recover rapidly from a standdown.[3] Finally, there are environmental concerns with each mix, such as impacts on the Earth's ozone layer from solid rocket fuel exhaust.

Within the risk category, there are at least three kinds of criteria. The first criterion is cost uncertainty in the estimates for recurring and nonrecurring costs.[4] The second criterion is technical risk in the development of new launch vehicles. The third is the schedule risk in both new developments and flying payloads on schedule. Schedule risk in turn is linked back to estimates of the resiliency of vehicle mixes, as found in the performance category.

Four criteria stood out in the policy category. The first was the desirability of new research and development, not only for new knowledge, but as a means of meeting other objectives such as lowering launch costs. The second criterion was concern over the impact to the shuttle system of any new development, for both current and future operations. The third, not surprisingly, was concern over the effect on existing ELVs from any new development. Finally, there was the question of whether a new heavy-lift capability should be developed. Such a capability was crucial in some traffic scenarios and irrelevant in others.

5.1.1 The Analytic Hierarchy Process

An obvious problem with the evaluation criteria selected above is how to weigh them against each other. How much should schedule risk be weighed against cost estimates, or environmental impacts against vehicle reliability? If a common metric such as dollars were available for all the criteria, then a direct comparison could be made. If there are no common metrics, then subjective judgments and tradeoffs can be made, as is common in the political process. In the case of space transportation, however, analytic comparisons and subjective judgments should be mixed in evaluating the various alternatives.

One approach to mixing subjective and quantitative judgments is to aggregate only those criteria with common measures (e.g., dollars or time). The decisionmaker is left to make the final, qualitative tradeoffs as best he can. A drawback to this approach is the sheer number of tradeoffs that might be required. One decisionmaker may be content with considering two or three "drivers" (such as the budget), whereas another would want to understand more of the available tradeoffs. Many of the arguments over space transportation stem from differences among decisionmakers as to the relative importance of various criteria and whether some factors are even worth assessing.

A decision support system has been developed to handle the evaluation of explicit, measurable criteria and "expert" judgment. Termed the "Analytic Hierarchy Process (AHP)" by its developer, Thomas L. Saaty, it is described in his book of the same name.[5] The central technique of AHP is the pairwise comparison of alternatives to elicit the relative preferences of evaluators. Because comparing more than two alternatives at a time is often difficult to do

[3]System resiliency and vehicle reliability relations are treated in App. D.

[4]A summary of cost risks from the STAS reports can be found in Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383, U.S. Government Printing Office, Washington, D.C., July 1988, p. 87.

[5]T. L. Saaty, *The Analytic Hierarchy Process*, McGraw-Hill, New York, 1980. A briefer introduction to AHP and a sample usage can be found in Scott Pace, *Assessing Options for Anti-Satellite Arms Control: The Analytic Hierarchy Process*, The RAND Corporation, P-7190-RGS, February 1986.

consistently, AHP requires only that the evaluator state a relative preference for one choice over another at any particular time.

The normal sequence for using AHP is a five-step process, as illustrated by the following application to the space transportation planning problem. The first step is to identify and summarize the various launch vehicle mixes the United States may pursue. The second step is to develop evaluation categories and measurable criteria, as done above. The third step is to to evaluate the launch vehicle mixes via AHP. This requires selected "experts" who are either actual or surrogate decisionmakers in space transportation planning to fill out structured questionnaires on the relative importance of the evaluation criteria through pairwise comparisons. In the fourth step, each evaluator makes separate pairwise comparisons of the launch vehicle mixes with respect to each individual criterion. These subjective evaluations are the raw data inputs to a separately developed AHP program which produces a single figure of merit for each launch vehicle mix.[6] This figure of merit is based on relative weights for each evaluation criterion as determined by the evaluators themselves.

The fifth step involves iterating the questionnaire and AHP evaluation process until a consensus ranking of the alternative options is achieved. Sometimes consensus is achieved quickly; sometimes several feedback rounds are required. The feedback consists of reporting the figures of merit (for each evaluator and for the group) for each option, reasons for differences in evaluation, and identified areas of contention and/or inconsistency. Individual evaluators may choose to change their subjective judgments on both criteria and weights and option preferences. At this point, areas of uncertainty (leading to inconsistent preferences) and disagreement (leading to divergent preferences) can be targeted for more detailed study. This focuses decisionmaking efforts on the areas of greatest need by identifying areas of agreement and reasons for disagreement. Final closure may in fact be less valuable than the process of working toward a consensus.

Figure 5.1 shows the evaluation criteria discussed above, grouped by evaluation category, and weighted by the author. As this reflects subjective judgments, it is not necessarily indicative of what actual decisionmakers would do. It does serve to illustrate, however, how evaluation criteria are combined by the AHP process. If decisionmakers disagree with the relative weights or the criteria themselves, the process allows them to see the impacts of their judgments and to modify them.

The most difficult problem with AHP arises from the evaluators themselves. Not all evaluators will have equal knowledge or insight, yet the process gives equal weight to the preferences of each of them. AHP also assumes the existence of an underlying preference "vector" (with magnitudes and directions) which is revealed through the pairwise comparisons. This is a powerful assumption which may at best hold only for the participating evaluators. The single figure of merit produced for each option is the result of subjective judgments and is not a purely analytic result.

Even with its limits and assumptions, AHP is a useful tool. It does not formulate the options or criteria for decisionmakers, but does provide a structured way of thinking about alternatives. It allows the combination of very different criteria while preserving the role of subjective judgment in making those tradeoffs (i.e., there are no hidden analytic assumptions about equating lives, dollars, time, etc.). Most importantly, it provides an audit trail for decisionmakers to see their areas of disagreement and uncertainty directly.

5.1.2 Using AHP in Space Transportation Planning

It might be expected that consensus among all evaluators would be impossible because their respective institutions would rate evaluation criteria differently. The Administration,

[6]Copies of the program and source code are available from the author.

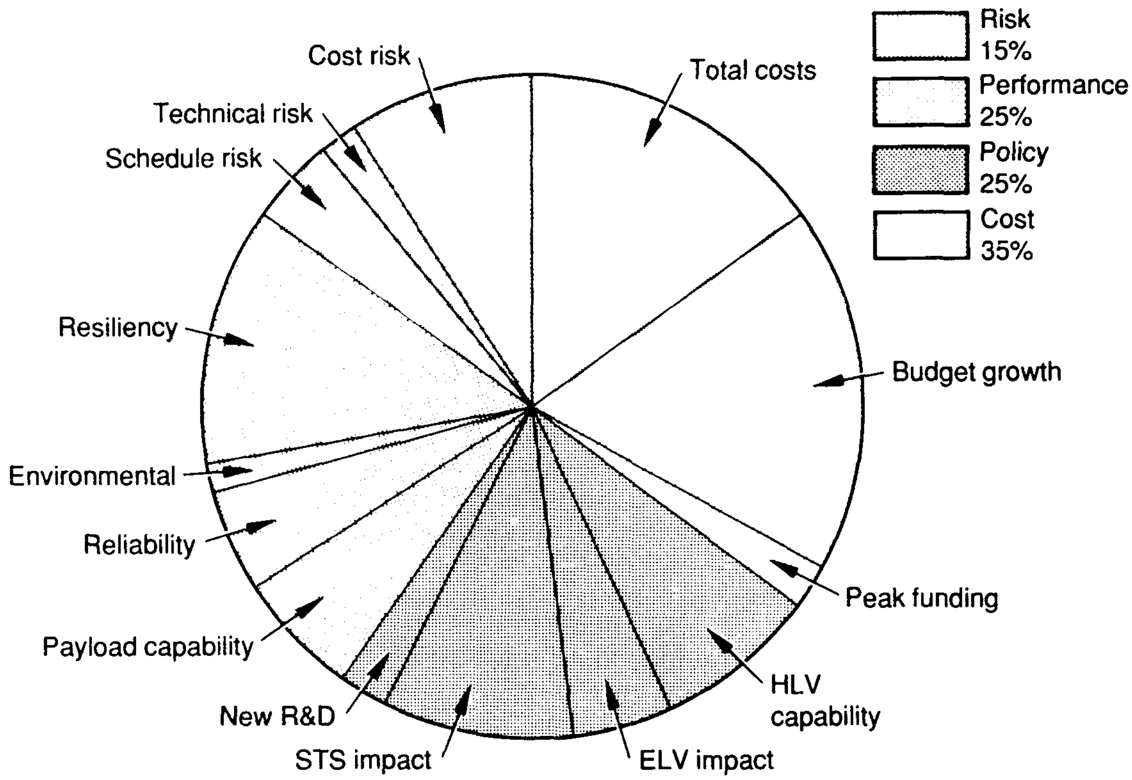


Fig. 5.1—Example combination of evaluation criteria by AHP

Congress, NASA, and the Air Force may come to a political agreement, but not necessarily because they have reached a common analytic understanding. AHP can promote consensus by fostering focused debate, but it cannot impose it. A practical modification for AHP is thus to group evaluators by institutions and not attempt to combine them. AHP cannot strictly be used to assign relative weights to the Congress, the Administration, NASA, and the Air Force since no overall evaluator exists who can represent the entire U.S. Government.

Consensus within institutions regarding preferable launch vehicle mixes depends on traffic demand assumptions. Different rankings of vehicle mixes might be produced for each baseline demand, leading to questions of how to evaluate launch vehicle options with respect to differing demand scenarios. Four choices are evident:

- Evaluate all options with respect to the four baseline demands;
- Evaluate only applicable options for each baseline demand;
- Evaluate all options while uncertain of actual demand level;
- No evaluations, just weigh the criteria by decisionmakers.

The first choice would be characterized by much redundancy and wasted effort. Only a few of the options are directly applicable to each demand level. It is useless to compare a vehicle mix for a constrained demand (e.g., STS only) to an expanded demand (e.g., an SDI deployment). The second option would filter out launch vehicle mixes not meshing with the demand levels. A similar process was done earlier (See Sec. 4.4) in comparing the costs for

applicable options to demand levels. This process could be continued and AHP used to include other criteria such as risk and policy concerns.

The third choice is the most realistic. At this point, it is unknown which demand level will occur. The United States could choose many variations on the baseline demand levels and only in retrospect would it be clear which was selected. In evaluating options for an uncertain demand, decisionmakers might place a premium on keeping options open for as long as possible and delay decisions until more information was available. Without commitment to a particular set of space goals, it is unlikely the United States would commit more than a few years ahead to a specific vehicle mix. In this situation, the important result of evaluating applicable options would be dates for making decisions. For example, how long might a heavy-lift vehicle decision be delayed, assuming a level of uncertainty as to which baseline demand will occur?

Evaluations might be abandoned altogether and decisionmakers or their surrogates simply asked to specify their evaluation criteria and relative weights. That result alone would be interesting to many analysts, including the decisionmakers themselves. Weighted criteria could then be used to evaluate the options applicable to each demand as described above, but without claiming them to be the choices of the decisionmakers. This has the added advantage of not asking them to endorse or correct independently posed estimates on costs, reliabilities, and other factors.

The last option, asking each decisionmaker to weigh the significance of potential evaluation criteria, was chosen. Weighted criteria and other interview results were combined with the analyses from Sec. IV to evaluate launch vehicle mixes. Like the second and third options discussed above, launch vehicle mixes were evaluated with respect to each level of demand and for the case of uncertain demand. In the conclusions, results from both analyses and interviews are discussed first, followed by observations from the interviews themselves.

5.2 INTERVIEW PROCESS

Based on an examination of the history and current status of space transportation policy, people were identified in government and industry who had experience in space transportation planning.[7] An initial list of over 60 names was compiled of those with substantive governmental responsibility for space transportation planning. Persons on this list were contacted by phone and letter to arrange half-hour to one-hour interviews. Efforts were made to include the most senior people available within time and budget limitations. This reduced the final list of interviewees to a little over 20 people, distributed across the Administration, Congressional staff, NASA, and the Department of Defense.

A pair of questionnaires was designed to structure the interviews and obtain the maximum benefits within time constraints. (Appendix F provides the questionnaires.) The objectives of the interviews were to:

- Identify and weight evaluation categories and criteria;
- Identify issues of concern over varying time horizons;
- Estimate the likelihood of different demand levels;
- Identify key areas of uncertainty to the decisionmaker.

Priority was placed on determining evaluation criteria and weights, followed by open-ended discussions of institutional issues, interagency politics, and uncertainties in planning space transportation systems.

Potential evaluation criteria, to be weighed by the interviewees, were grouped into six general categories:

[7]Scott Pace, "U.S. Space Transportation Policy," *Space Policy*, November 1988, pp. 307–318.

- Policy issues
- Mission implications (specific missions or tasks to be done)
- Cost (of launch vehicles and payloads)
- Performance (e.g., payload capacities)
- Operational risks (e.g., reliability and safety issues)
- Programmatic risks (e.g., cost overruns and schedule slips)

Interviewees were encouraged to add their own criteria and ignore those they felt to be irrelevant. Some individuals combined categories, such as policy and mission implications, whereas others might ignore a category completely.

The interview results are grouped by major institutions. The interviews focused on institutional views, albeit through individual perspectives, and thus individual responses are not identified. In compensation for such anonymity, a strong attempt was made to be as comprehensive as possible in representing each institution. Institutions are not monolithic and diverse views are possible depending on which part is addressed (e.g., within Congress, the House Armed Services Committee and the House Committee on Science and Technology often have different views on space policy).

The number of interviews conducted is too small to serve as valid statistical sample of opinion. On the other hand, the number of those in the government with space transportation responsibilities is low enough that the 20 or so interviewed do constitute a significant proportion of the relevant policy community.

5.3 INTERVIEW RESULTS

While most persons appreciated the anonymity condition, few explicitly asked for it and none asked for more than verbal assurances that the work was not for public attribution. All interviewees were interested in t ing at length, although some found the questions difficult and spent considerable time in gi...g thoughtful responses (for which the author is grateful). No other analyst had structured the issue of space transportation planning in this way, particularly in combining subjective, institutional perspectives with independent analytical work. All interviewees agreed that analytic results, while interesting, were only one component in the implementation of space transportation decisions. Interviewees were interested in receiving feedback on the final results in order to understand others' perspectives and the basis for those perspectives.

The remainder of Sec. V covers the general perspectives of the major institutions and the relative weights each gave to the evaluation criteria groups. In the tables listing the relative group weights, specific evaluation criteria are listed within each group. Only those criteria cited by two or more interviewees are listed, with the most common criteria listed first.

5.3.1 The Administration

The interviews took place after the November 1988 national elections, and thus it was difficult to cite the space transportation policies and priorities of the new Administration. Statements made during the campaign indicated that a Bush Administration would continue to support manned spaceflight, a commercial ELV industry, and the space station program. Its commitment to more ambitious civilian goals was unclear, although some preference seemed to exist for new manned lunar missions before a commitment to a manned Mars mission. SDI was strongly supported as a research program, but actual deployment decisions were left for the future.[8]

[8]"George Bush on Space—Fact Sheet," Bush-Quayle 88, press release, October 3, 1988.

Lacking definitive guidance on the choices of the President-elect, interviews were conducted with members of the Executive Office of the President (EOP), such as the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), the National Security Council (NSC), and former Reagan Administration officials. Their views were combined to give a picture of space transportation concerns from an Executive Branch viewpoint.

As might be expected, Administration officials and ex-officials were concerned with broad policy issues such as perceptions of U.S. space leadership, the competitiveness of the commercial ELV industry, and budget deficit pressures on the U.S. space program. There was a strong feeling that while the United States has a "full plate" on the one hand with shuttle operations and deploying the space station, it has not yet made fundamental decisions as to what it wants to accomplish in space. Interviewees felt that the lack of such decisions will be important in upcoming budget battles. The level of demand termed "constrained" in Sec. III was seen by many as a likely "nominal" outcome. Other higher levels of demand were seen as optimistic for at least the next 10 years.

Table 5.1 shows the average relative weights for each evaluation category and the most commonly mentioned evaluation criteria within each category.

5.3.2 NASA

NASA shares many of the policy concerns of the Executive Office of the President, especially budgetary ones. Possibly of greater long-range importance is the belief that the operational demands of both the shuttle and space station programs will absorb most if not all of NASA's attention over at least the next decade. This, combined with budgetary limits, may result in no new initiatives. Many NASA managers share a desire to "take the lead," to initiate major new technology programs, to support new space and planetary science missions, and to expand manned missions beyond Earth orbit to the Moon and Mars. However, NASA's desires to be proactive, rather than reactive, are seen as increasingly difficult to satisfy due to budget limits and competition from other government priorities.

NASA Headquarters does not always present a unified front to other institutional players, thus hindering its ability to negotiate agreements on budgets and programs. One example of this is the Shuttle-C program as viewed from the Office of Space Flight (Code M) and the Office of Space Station (Code S). Code M would like to build the Shuttle-C for a variety of reasons, such as conserving shuttle flights, increasing the utilization level of shuttle infrastructure, and providing an unmanned test bed for shuttle improvements (e.g., liquid rocket booster strap-ons). The major mission justification to date, however, has been the deployment of the space station. Shuttle-C proponents argue that using its higher capacity in cooperation with shuttles would reduce the number of flights for the space station's deployment over using shuttles alone. This in turn would likely reduce the cost and risk of the deployment sequence. Code S would probably use a Shuttle-C if one were available, but they are reluctant to design payloads for a vehicle that may not come into being. More critically, they do not want to add the Shuttle-C's development cost to the already large (and growing) cost estimates for the station. In their view, a Shuttle-C could be the political straw that breaks the Congressional camel's back, further eroding support for the space station.

Table 5.2 shows the average relative weights for each evaluation category and the most commonly mentioned evaluation criteria within each category.

5.3.3 Congress

Interviews for this institution concentrated on Congressional staff with oversight responsibilities on key House and Senate committees affecting space funding, such as the

Table 5.1
SELECTED CRITERIA AND WEIGHTS FROM INTERVIEWS WITH THE EXECUTIVE OFFICE OF THE PRESIDENT (N = 4)

Policy: 31 percent

1. Perception of U.S. leadership in space transportation
2. Support for U.S. commercial ELV industry
3. Opportunities for new technology R&D
4. Future of the STS and manned spaceflight

Mission Implications: 20 percent

1. Supports space station deployment and operations
2. Continues/expands U.S. manned spaceflights

Cost: 16 percent

1. Politically feasible percentage funding increase each year
2. Minimum nonrecurring costs (upfront)
3. Minimum peak year funding requirement
4. Minimum life-cycle costs

Performance: 10 percent

1. Maximum operational availability
2. Payload capacity consistent with demand

Operational Risk: 12 percent

1. Maximum launch vehicle reliability
2. Minimum standdown times and maximum surge capability
3. Safety for involved personnel
4. Environmental acceptability

Programmatic Risk: 11 percent

1. Minimum technical risk of the launch vehicle mix

Senate Armed Forces Committee and the House Science and Technology Committee, as well as related appropriations committees. In addition, Congressional advisory groups such as the Office of Technology Assessment (OTA) and the Congressional Budget Office (CBO) were included. While the views of staff do not necessarily reflect the views of members, their opinions can indicate areas of interest to the members, and what advice members will get from those closest to them.

Budget issues and potential compromises dominated the thinking of virtually all the staffers. Among the NASA-related committees there was concern that the challenges of the shuttle and space station program would crowd out other space activities. Among the DoD-related committees there was concern over potential problems with current purchases of ELVs. Many military payloads have been moved from the shuttle to these vehicles, most of which are new, upgraded designs which have yet to become operational. The Titan 4 program, in particular, was cited by several individuals as a potential national security "disaster" if it experienced major delays or failures.

Table 5.2
SELECTED CRITERIA AND WEIGHTS FROM INTERVIEWS
WITH NASA HEADQUARTERS (N = 5)

Policy: 25 percent

1. Perception of U.S. leadership in space transportation
2. Opportunities for new technology R&D
3. Future of the STS and manned spaceflight

Mission Implications: 14 percent

1. Provides a heavy-lift launch capability
2. Supports space station deployment and operations
3. Continues/expands U.S. manned spaceflights
4. Supports new civil space initiatives

Cost: 18 percent

1. Minimum total annual growth rate
2. Minimum peak year funding requirement
3. Minimum nonrecurring and recurring costs

Performance: 9 percent

1. Maximum operational availability

Operational Risk: 22 percent

1. Maximum launch vehicle reliability
2. Minimum standdown times

Programmatic Risk: 13 percent

1. Minimum technical risk of the launch vehicle mix
2. Availability of industrial infrastructure
3. Minimum schedule risk
4. Minimum life-cycle cost risk

There was a recognized need for statements of budgetary priorities from the Administration, especially in defining what the United States should be doing in space, yet at the same time a consensus that new starts would be virtually impossible in the face of other expected budget cuts. Budgetary limits, according to the staff, mandated an integrated space plan by NASA and the Department of Defense.[9] While intellectually supporting the idea of separate civil and military programs, they felt that budget pressures would argue for closer cooperation and commonalty in launch systems.

Most staffers argued against building vehicles in anticipation of new payload requirements, preferring to let launch vehicles respond to payload needs as they occurred. There was little support for the idea of building new launch vehicles to shape the payload market. Like EOP interviewees, they considered the constrained traffic demand level to be the most probable outcome, as opposed to the nominal demand.

[9] "Fiscal year 1989 funding for the Air Force's space booster program could be frozen," *Space Business News*, July 25, 1988, p. 5.

There was widespread support for the commercial ELV industry from both a national security and economic competitiveness perspective. Although a return to a mixed fleet was uniformly welcomed, there was still support for improving the shuttle's capabilities, as with the Advanced Solid Rocket Motor (ASRM) program and extending the time a shuttle orbiter could stay in space.

Table 5.3 shows the average relative weights for each evaluation category and the most commonly mentioned evaluation criteria within each category.

5.3.4 Department of Defense

The Department of Defense, especially the Air Force, is most concerned with the need to launch their current backlog of payloads. This backlog, stemming from the string of launch vehicle failures in 1986, has resulted in a preponderant emphasis on launch vehicle reliability and availability. Many DoD planners cited DoD policy in achieving "assured access to space" as the impetus behind their concerns, but stated policies were also reflective of more basic, institutional motivations.[10] DoD launch needs are seen, and treated, as national security requirements of overriding importance. These requirements in turn arise because the Department of Defense has "operational" requirements to be in space. In contrast, NASA's needs are uniformly seen as largely "discretionary." Some DoD planners noted, however, that if NASA deploys a space station, it will then have an "operational" requirement in maintaining that facility.

It is not surprising that the Department of Defense would see its own missions as being of greater importance than NASA's, but differences between the two perspectives go deeper than that. DoD planners point to the long and complex sequence of requirements development and acquisition reviews that are involved in their space programs (usually in a string of acronyms such as SONs, POMs, DSARCs, DRBs, and FYDPs). In contrast, NASA planning was often characterized as "NASA deciding what it wants and then going out and getting it," without somehow certifying that chosen missions are in the national interest.

Conflicts with NASA seem to have been more divisive in recent years, with many DoD interviewees looking to the past for examples of closer cooperation. In part this may reflect greater budgetary limits on the aspirations of the civil and military space sectors, but personalities seemed to have played a large role as well.[11] Current assessments by the Department of Transportation (DOT) on developing private "spaceports" for commercial ELV launches are seen as a potential "raid" on DoD property and assets at Vandenberg AFB in California and Patrick AFB in Florida. The Air Force takes great pride in its space recovery efforts which have led to invigorating the U.S. ELV industry, yet it sees itself as surrounded by many inexperienced competitors for its space-related assets.

DoD concentration on operational problems corresponds to a concern with recurring costs. The defense budget is seen as growing only slowly if at all and the space sector is not likely to have the same rate of growth as it has had for the past six years. Like NASA, the Department of Defense sees the prospect of new starts as slim and thus pressure exists to hold down recurring costs in order to provide some planning flexibility. Also like NASA, many DoD planners prefer to be proactive rather than reactive in launch vehicle development. The Advanced Launch System, and to a lesser extent the National Aerospace Plane, are seen as desirable but unlikely to result in usable vehicles in the next decade because of budget limitations.

[10] Department of Defense, *Department of Defense Space Policy*, Washington, D.C., March 10, 1987.

[11] For example, NASA Administrator James Beggs and his Deputy Hans Mark (a former Secretary of the Air Force) were perceived as having a "go-for-broke" style that left little room for negotiation and compromise.

Table 5.3

SELECTED CRITERIA AND WEIGHTS FROM INTERVIEWS WITH CONGRESSIONAL STAFFS (N = 6)

Policy: 24 percent

1. Relative size of NASA and DoD budget
2. Perception of U.S. leadership in space transportation
3. Relative roles of DoD and NASA in peacetime launches
4. Opportunities for new technology R&D

Mission Implications: 16 percent

No agreement on any specific missions, other than meeting existing requirements.

Cost: 26 percent

1. Minimum total annual growth rate
2. Minimum life-cycle costs
3. Minimum peak year funding requirement

Performance: 16 percent

1. Maximum operational availability
2. Payload capacity consistent with demand
3. Maximum flexibility for future performance upgrades

Operational Risk: 11 percent

1. Maximum launch vehicle reliability
2. Safety for third parties and involved personnel
3. Availability of alternative vehicles for payloads
4. Surge rates and environmental acceptability

Programmatic Risk: 7 percent

1. Minimum life-cycle cost risk
2. Minimum schedule risk

Many members of the Defense Department would like to see the United States acquire a heavy-lift vehicle, capable of placing 100,000 lb or more in low Earth orbit on a single launch. While a Shuttle-C could provide that capability, they are not enthusiastic over using a NASA-owned vehicle. They fear another shuttle failure could force a standdown of both manned and unmanned shuttle components, and thus they would prefer an "independent" heavy-lift vehicle. That would require a new development program, however, which Congress is reluctant to fund. Congress would welcome a unified position from the DoD and NASA where both would use the same vehicle, but such an agreement would require NASA and DoD to reach internal agreements before they could enter into an external one.

The average relative weights for each evaluation category and the most commonly mentioned evaluation criteria for each category are shown in Table 5.4.

Table 5.4

SELECTED CRITERIA AND WEIGHTS FROM INTERVIEWS WITH DEPARTMENT OF DEFENSE AND AIR FORCE OFFICIALS (N = 7)

Policy: 5 percent

1. Relative roles of DoD and NASA in peacetime launches
2. Relative size of NASA and DoD budget
3. Perception of U.S. leadership in space transportation
4. Support for U.S. commercial ELV industry

Mission Implications: 17 percent

1. Performing current military and intelligence missions
2. Being able to support wartime needs
3. Providing incentives for smaller, more numerous payloads
4. Supporting new, non-SDI military missions

Cost: 25 percent

1. Minimum recurring costs
2. Minimum life-cycle costs
3. Minimum nonrecurring costs

Performance: 15 percent

1. Maximum operational availability
2. Payload capacity consistent with demand
3. Maximum flexibility in handling upper stages
4. Cross-compatibility with the STS

Operational Risk: 31 percent

1. Maximum launch vehicle reliability
2. Minimum vehicle standdown times
3. Maximum surge rates
4. Environmental acceptability

Programmatic Risk: 7 percent

1. Minimum technical risk in the launch vehicle mix
2. Minimum recurring cost risk in operations
3. Maximum ability to change capabilities during development

5.4 FUTURE TRAFFIC DEMAND AND LAUNCH VEHICLE CHOICES

Whereas each group of decisionmakers emphasized different concerns in their selection and weighing of evaluation criteria, there was rough agreement on probable demand levels. Table 5.5 shows the average ranking each institutional group gave to the four demand levels defined in Sec. 3.3.

Interviews with those in the Executive Office of the President saw nominal demand levels occurring with a subjective probability of 50 to 60 percent, whereas major expansions such as new civil initiatives or an SDI deployment were cast as having a 0 to 10 percent probability.

Table 5.5

RELATIVE RANKING OF EXPECTED SPACE TRAFFIC DEMAND LEVELS
(1 = most likely, 4 = least likely)

Institution	Con-strained	Nominal	Expanded Civil	Expanded DoD
EOP (n = 4)	2	1	2	4
NASA (n = 5)	3	1	2	4
Congress (n = 6)	1	2	3	4
DoD (n = 7)	2	1	3	4
Composite (n = 22)	2	1.25	2.5	4

Interviews with those in NASA gave nominal demand levels a 80 to 85 percent chance, but varied widely on the chance of experiencing very constrained demand levels. They also gave SDI deployments a low probability of around 10 percent.

Congressional staffs were more pessimistic about being able to afford nominal levels of demand. They saw constrained levels as having a slightly greater chance of occurring. They were even more pessimistic about the chances for SDI deployment, giving it a negligible chance for at least the next decade.

DoD officials gave nominal demand levels a slightly greater chance of occurring than constrained demand levels. New civil initiatives and SDI deployments were seen as equally unlikely by wide margins compared to nominal and constrained levels, with SDI being seen as slightly behind civil initiatives in probability.

5.4.1 Choices of Launch Vehicles

When asked how the United States should (or could) respond to meeting a given level of demand, there was broad agreement among the interviewees for the cases of constrained, nominal, and expanded DoD demand levels.

If it were known that the United States would be launching only 10 to 15 equivalent shuttle flights per year, with no DoD new starts and cancellation of the space station, most interviewees felt the United States would still maintain a mixed fleet. Shuttle flights would be reduced to 5 to 6 per year with ELVs meeting the rest of the demand.

The most common response to meeting a nominal demand level of about 20 to 30 equivalent shuttle flights would be to maintain the shuttle flight rate at currently planned levels and meet demand through additional purchases of ELVs. Building the Shuttle-C was a second choice for everyone and its construction depended on having NASA come forward with a mission requirement (such as the space station). The Department of Defense saw no requirement for a Shuttle-C. The ALS program would remain a technology program at this demand level, with (it is hoped) spinoff benefits to existing ELVs.

Assuming the United States commits to a major new civil initiative, such as a return to the Moon or a manned mission to Mars, there was a wide range of responses on the question of appropriate launch vehicles. Executive Branch, Congressional, and most DoD interviewees felt the ALS program should move to full scale development (FSD) with vehicles from the ALS "family" eventually taking over from most U.S. ELVs. The shuttle itself would be retained as the means of manned access into space, and some smaller ELVs might be

retained as well. A few DoD planners thought that the Shuttle-C might be developed first to meet NASA's near-term needs and then as demand projections solidified, ALS vehicles would supplant Shuttle-C. In their view, this had the added benefit of reducing possible schedule pressures on the ALS program.

If the United States decided on a major expansion of its military space assets as with an SDI deployment, there was uniform opinion that the United States would also proceed with developing ALS vehicles. There was much less support for pursuing both a Shuttle-C and ALS development as it was felt that both systems would be redundant and too costly to maintain. The near-term availability of the Shuttle-C was not seen as a significant advantage compared to expected payload development times.

5.4.2 Launch Vehicle Choices Under Uncertainty

In actuality, traffic demand levels are not known with certainty. The decisionmakers interviewed were in rough agreement on the likelihood of various demand levels, but realized they must develop contingency plans should circumstances change. Some of the more interesting discussions resulted from questions on what they would recommend given the uncertainty surrounding actual demand levels for 1990–2010.

The dominant uncertainties for those interviewed were the budget deficit and the policy directions to be chosen by the Bush Administration. The budget deficit and presidential leadership were also viewed as linked problems.

Beyond the near term, the dominant uncertainties were the role of international cooperation with the Soviets (if any) and U.S. allies and technological progress in the ALS and NASP programs. Even assuming budget problems are brought under control, there remained uncertainty as to what the United States would choose to do in space. NASA officials would clearly like to see new civil initiatives, yet they are more concerned with maintaining shuttle operations and building the space station. DoD space planners would like to see new military initiatives in space, especially in meeting expected warfighting needs irrespective of SDI. They, too, however, are preoccupied with performing current military missions in a tight fiscal environment. Furthermore, they have yet to settle crucial questions on the roles and responsibilities of the Services and the unified and specified commands.

Most interviewees supported the current mixed fleet plans and saw ELVs as a way of adapting to variations in demand through the 1990s. Given budget realities, there was little expectation that the ALS program would move beyond technology development for many years to come. Whereas some advocated "biting the bullet" and committing to development now, others took a "wait and see" attitude. Major new missions that might justify increased funding for new launch vehicles (e.g., an SDI deployment) were seen as unlikely before the turn of the century.

The future of manned spaceflight was an interesting separate question. Current NASA plans for the four orbiter fleet call for 12 to 14 flights per year. Except for NASA, most interviewees (especially in Congress) thought achieving 8 to 10 shuttle flights per year was more realistic. For comparison, the most manned flights performed in a year was in 1985 when the United States launched nine shuttle flights (see Fig. 5.2). Although the Soviets annually launch many more vehicles than the United States, and their manned flights last longer, they do not have a major lead in the task of launching manned vehicles (i.e., the United States has launched 56 manned flights compared to 63 by the Soviets). Thus, a U.S. manned flight rate of 12 to 14 flights per year would be a major achievement.

Whereas some individuals hope the NASP program will provide a lower cost means of placing cargo into space, others focus on its potential application in manned transportation to and from space. Many cautioned that, as an experimental program, NASP cannot yet be considered a replacement for the shuttle. In turn, this means the shuttle or its variants are

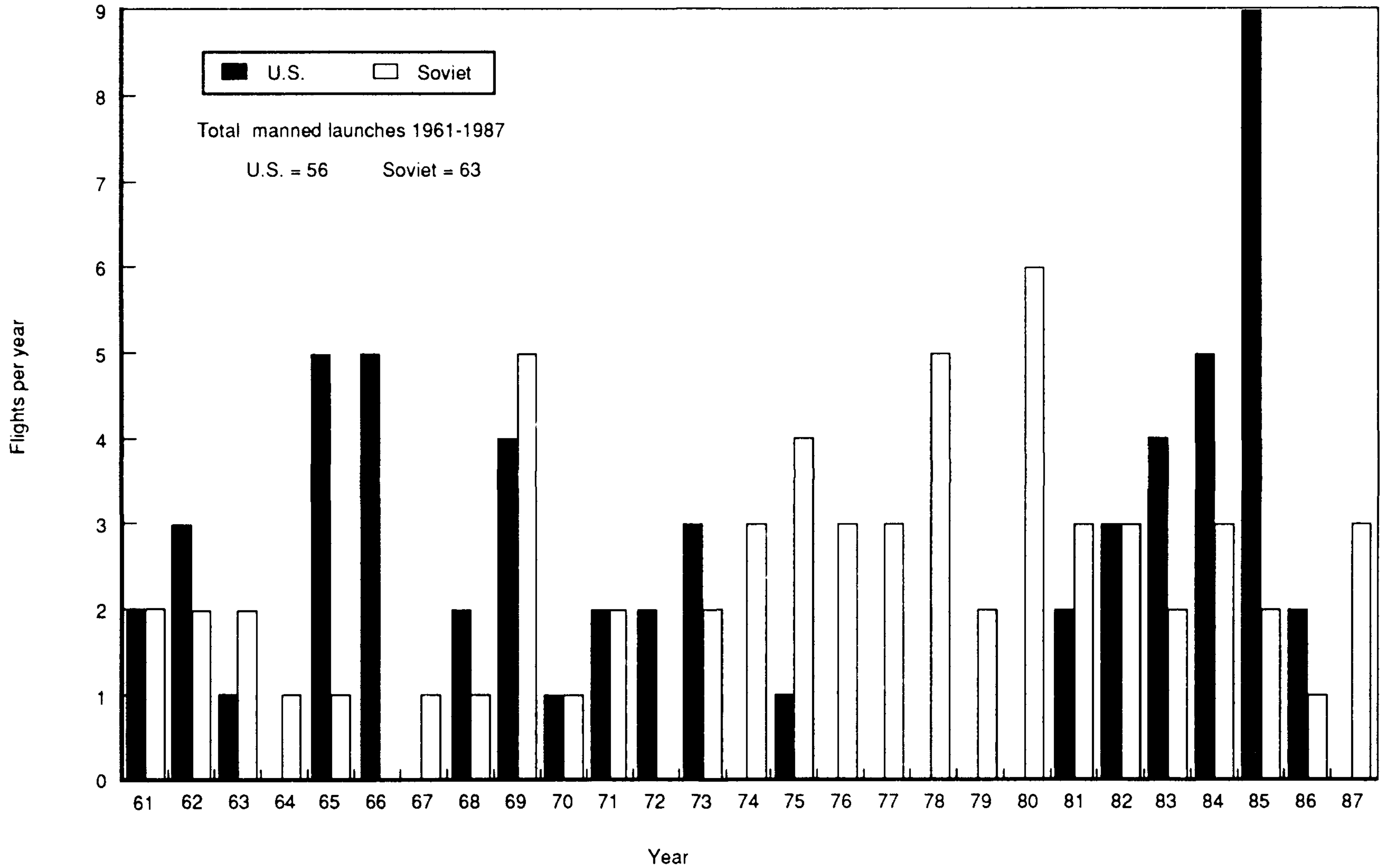


Fig. 5.2—U.S. and Soviet manned spaceflights

going to remain operational for many years to come.[12] Shuttle lifetimes can be extended by off-loading payloads to ELVs and the Shuttle-C. The shuttle's operational effectiveness can also be increased through evolutionary improvements (e.g., the ASRMs, additional electrical power for the orbiter, and avionics upgrades). These efforts are likely to take up much of NASA's attention in space transportation prior to new technologies becoming available to replace the shuttle fleet.

5.5 SUMMARY

In looking across all criteria categories, major differences between interview groups are readily observable. Figure 5.3 is based on the percentage weights cited in Tables 5.1 through 5.4 above.

The average criteria weights given by each group of interviewees reflect their views as derived from open-ended discussions. As expected, persons from the Executive Office of the President were most concerned about policy issues and the mission implications of launch vehicle mixes. They paid less attention to technical performance and programmatic risk issues, seeing those as the responsibility of the Department of Defense or NASA.

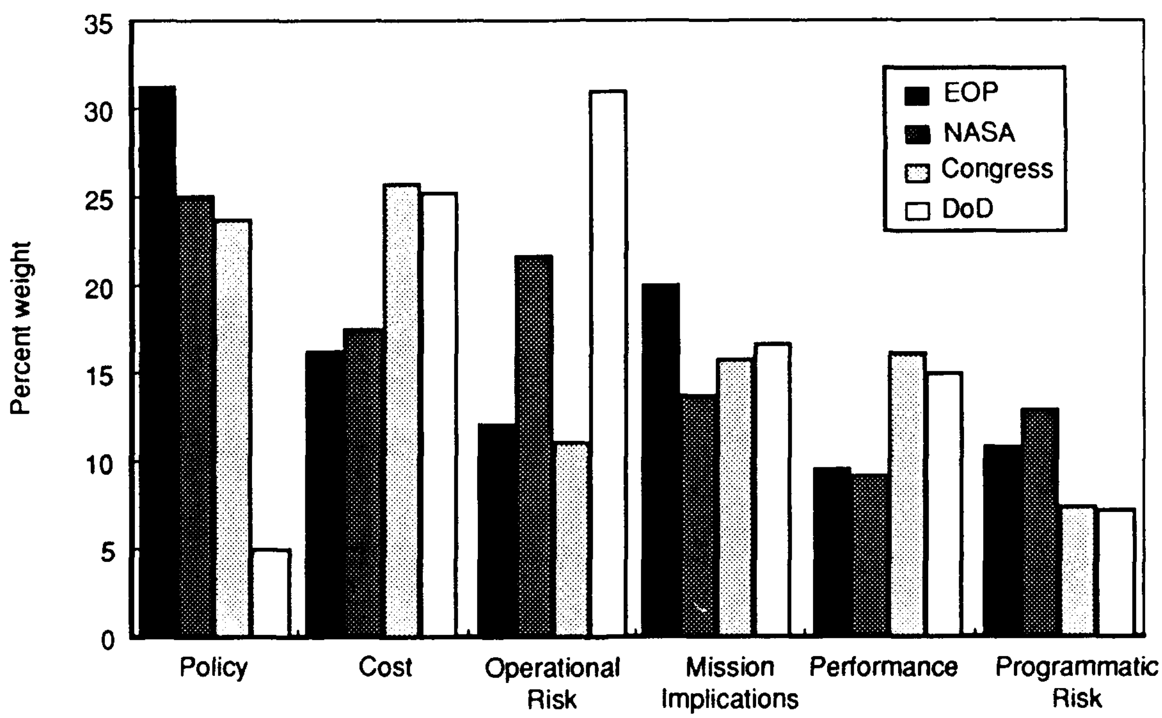


Fig. 5.3—Average evaluation criteria weights by major organization, December 1988

[12] The Boeing company is reputedly working on a manned version of an ALS vehicle which may supplant shuttle flights. Interview with Office of Technology Assessment, December 1988.

If the Bush Administration were to pick a launch vehicle mix largely on the basis of policy issues, it would first have to decide which level of space traffic it is willing to support. The achievement of U.S. goals in space would have to be traded off against competing plans to reduce the federal deficit. This would argue that expanded demand levels are unlikely and the resulting launch vehicle mix will be some combination of shuttle and ELV flights. Policy support for the mixed fleet is strong enough to make either an all-ELV or an all-STS fleet very improbable.

Congressional staff and analysts were most concerned with the linkage of policy issues and costs. Decisions on each both drive and constrain the other. The continual challenge of making tradeoffs in the budget process shaped much of these respondants' perspective and they were least concerned with programmatic risk and operational risk issues. These areas were seen as difficult to define and the responsibility of the cognizant agencies, much as the Executive Branch viewed it. The lower emphasis given operational risk issues was slightly surprising. Most interviewees felt the topic was important, but very complicated and often not relevant in the budgetary processes that they confronted on a day-to-day basis.

The Congress would likely find itself in agreement with the Administration on the pressures of the budget and restrict feasible launch vehicle mixes to the STS and ELVs. In the longer term, Congress would support expanded levels of civil demand before supporting an SDI deployment, while subsequently picking the most cost-effective mix.[13] This would favor the ALS family of vehicles.

The Department of Defense, in contrast to the Congress, gave the greatest emphasis to operational risk issues. The Challenger accident and standdown left them with a large payload backlog, delaying many national security missions. They have made a major effort in their space recovery plan to procure a diverse mix of expendable launch vehicles. In large part, this can be attributed to a lack of operational confidence in the shuttle, as well as reductions in the shuttle's post-accident flight rate (which limits launch opportunities). Like the Congress, the Department of Defense is also concerned with cost issues. They saw increasingly difficult tradeoffs occurring in the DoD budget, a viewpoint shared with many of the Congressional staffs.[14]

Pentagon interviewees at the Office of the Secretary of Defense (OSD) and Air Staff level gave less weight to programmatic issues and policy issues. Programmatic concerns were seen as the responsibility of particular program offices and the commands (especially the Air Force's Systems Command). The lack of weight given to policy seemed to reflect a position that the interviewees did not make policy, but rather implemented it. Existing space missions dominated their attention and those missions already had firm, bipartisan policy support. Thus, policy issues were not a major factor to them at this time. Several interviewees stated that their operational requirements had to be met while NASA's missions were more discretionary and thus subject to policy debates.[15]

The Department of Defense prefers to use ELVs except for certain shuttle-unique payloads, consistent with their emphasis on minimizing operational risk. Whereas STS reliability may be as good or better than ELVs, other factors such as standdown times and planning flexibility support use of ELVs. DoD interest in controlling costs, especially recurring costs, reinforces their lack of interest in Shuttle-C. If expanded demand levels transpired, the Department of Defense would prefer to develop and use ALS vehicles in the expectation of lower recurring costs and greater operational availability.

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[13]This preference for civil demand assumes no increase in the perceived threat from Soviet or third country ICBMs that would provide a stronger impetus for deployment of strategic defenses.

[14]This does not mean, however, that they would find themselves in agreement on budgetary priorities.

[15]Part of the problem is a difference in definitions. The military definition of "mission" refers to a general purposeful task such as reconnaissance that may be performed by a space system. In contrast, NASA uses the term "mission" for specific flights that may or may not be part of a larger effort. The Viking mission to Mars, for example, was part of a larger NASA program of planetary exploration.

NASA was most concerned about policy and operational risk issues. Emphasis on the latter is easy to understand, given the backlog of missions to be flown and the importance of transportation to the space station program. NASA interviewees recognized the importance of presidential initiative and interest to the civil space program and thus the importance of top-level policy support. Concern at Headquarters with policy issues tended to dilute emphasis on technical performance and programmatic risk issues, paralleling the same emphases given by the Executive Branch interviews. From a NASA Headquarters perspective, these issues are more appropriately addressed at the field center level.

For NASA, major policy choices as to the purposes of space transportation are almost as important as what demand level transpires. The development of space transportation systems and related technologies has been an important hallmark of NASA's identity, whereas the Air Force has usually taken a more utilitarian view. Traffic demand uncertainty means decisions on using an ALS or Shuttle-C for future payloads cannot be resolved by simple criteria such as cost-effectiveness. Other issues such as institutional leadership and the fulfillment of organizational commitments also play a role.

NASA would prefer an expanded civil demand traffic level. They would then confront a choice of supporting either a Shuttle-C or an ALS heavy-lift vehicle flying below its full capacity. Ironically, if NASA succeeded in getting an expanded civil demand, the most cost-effective option would likely be the largely Air Force-developed ALS. The Shuttle-C imposes significant costs that might be justified only at nominal demand levels in performing specialized missions, such as a test bed for shuttle improvements or space station deployment.

The following section on the evaluation of launch vehicle options summarizes key launch vehicle characteristics, as well as compares alternative launch vehicle mixes. The options are compared on the basis of the evaluation criteria discussed in Sec. 5.1, the results of performance and cost analyses from Sec. 4.3 to 4.5, and the institutional factors described here. The best launch vehicle mix is selected for each level of demand, and recommendations are made for planning given uncertainty over actual future demand requirements.

VI. EVALUATION OF LAUNCH VEHICLE OPTIONS

6.1 THE SPACE TRANSPORTATION PLANNING PROBLEM

The purpose of this report has been to evaluate launch vehicle combinations capable of meeting a range of U.S. space traffic needs between 1990 and 2010. The purpose of the evaluation is to clarify alternatives available to the United States in pursuing potential national goals and to assist the government in understanding the implications of those alternatives.

The study addressed two policy-level questions. The first question was: "Which launch vehicle options are best for the United States?" In interviews with space transportation planners, it was clear that institutions held diverse views on what was "best" for themselves and for the United States as a whole, thus leading to a combination of diverse evaluation criteria with uncertain space transportation requirements.

The second question was: "What and when are the decision points for choosing the best option?" Different decision points can be expected depending on specific assumptions made as to future levels of space traffic, national policy directives, and changing technical conditions. In the event traffic demand and policy guidance are unclear, recommendations are made on which launch vehicle options should be discarded and which should be held open.

Based on known launch vehicle alternatives, the two policy-level questions above were extended into a series of questions about specific programs:

- Should the United States purchases more ELVs to support civil and national security space goals?
- Should the United States build a Shuttle-C?
- Should the United States continue the ALS program without either a commitment to deploying strategic defenses or expanding civil space efforts?
- How should the United States plan for manned access to space beyond the space shuttle?

No recommendations are made as to which goals the United States should pursue in space. Rather, recommendations on launch vehicle choices are made for cases where future space traffic is given (a policy choice has been made) and for where it is uncertain (where policy choices are deferred). The report thus evaluates the preferable means of space transportation for a range of purposes.

6.2 APPLYING EVALUATION CRITERIA TO ALTERNATIVE LAUNCH VEHICLE MIXES

Various launch vehicle mixes have been addressed in terms of their performance and cost characteristics. The individual launch vehicles used in the mixes are summarized in Table 6.1. They are launch vehicles already in use, soon to be introduced, or currently under study. Some systems were left out because they could not lift significant amounts of likely payloads (e.g., the Scout); others were excluded because of their technical immaturity (e.g., space-lift versions of the National Aerospace Plane).[1] The cost and reliability numbers shown are those used in the assessments (see Sec. IV).

[1]Some decisionmakers may disagree with these assumptions. For example, there may be a transformation in payload design, shifting missions onto smaller, less expensive satellites that could then be lifted by Scout-class

Table 6.1

SUMMARY OF ALTERNATIVE LAUNCH VEHICLES

	Launch Vehicle						
Key Characteristic	Shuttle	Delta	Atlas	Titan 2	Titan 4	Shuttle-C	ALS HLV
Payload capacity (lb)	55.5K	11.4K	14.9K	5.2K	39.1K	120K	150K
Recurring cost per flight	$245M	$35M	$71M	$48M	$163M	$520M	$150M
Cost per payload pound	$4.4K	$3.1K	$4.7K	$9.2K	$4.2K	$4.3K	$1.0K
Reliability	.99	.96	.95	.92	.95	.98	.98
Average stand-down (mo)	12	4	4	6	6	8	3
Flight rate (per year)[a]	7–14	2–6	1–6	0–3	4–12	0–3	0–32
Nonrecurring costs[b]	0[c]	0	0	0	0	$1.2B	~$11B
Primary government user	NASA	DoD	DoD	DoD	DoD	NASA	DoD?

NOTE: K = thousand, M = million, and B = billion.
[a]Flight rate range includes all demand levels.
[b]Existing vehicle development costs are sunk.
[c]A new orbiter would cost ~$2.1 billion.

In Sec. 4.3, alternative launch vehicle mixes were proposed for each representative demand level. Table 6.2 summarizes the alternatives in terms of their undiscounted costs and expected loss rates.[2] The cost of launch vehicles for the 1988–1995 manifest was calculated at $36 billion. Beyond 1995, U.S. space traffic demand may move in a variety of directions. Launch vehicle costs for serving this demand were calculated to be in a range of $70 billion-$159 billion.

Launch vehicle costs were unadjusted for mission risk, such as launch failures. The costs are thus optimistic and likely to be higher in reality. Based on historical and projected vehicle reliabilities, expected payload losses were calculated for each mix of vehicles. The percentages were based on units of "STS equivalents" (see Sec. 4.5) and full shuttle cargo bays.

Budget growth rates to support these mixes of payloads and launch vehicles were roughly calculated for the 1988–2010 period. (See Sec. 4.4). As can be seen in Table 6.2, the expanded demand levels require significant real annual growth rates.[3]

vehicles. There may also be technical breakthroughs in the NASP program that could make a NASP-based replacement of the shuttle a nearer term possibility.

[2]See Secs. 4.4 and 4.5 for how these estimates were made.

[3]Payloads were assumed to cost an average of $10,000 per pound. Satellites may cost from under $10,000 to over $60,000 per pound. But launch vehicles are not filled with satellites. There is dead space ("manifest margin"), upper stages, on-board fuel, support cradles, etc. that dilute the actual cost per pound of the entire cargo. Some analysts refer to the satellites only as payload while others use payload to refer to all material in the cargo area. The latter convention is used here.

Table 6.2

SUMMARY OF ALTERNATIVE LAUNCH VEHICLE MIXES, 1988–2010

Option		Launch Vehicle Costs (1988 $)	Average Launch Cost per Payload Pound	Expected Total Losses (STS Equivalents) (1966–2010)
0	Manifest 1988–1995	$ 36 billion	$5300	
	Constrained demand			
1	STS/ELVs	$ 79 billion	$5500	1.6%
2	All STS after 1995	$ 82 billion	$5700	0.6%
3	All ELVs after 1995	$ 70 billion	$4900	2.7%
	Nominal demand			
4	Current STS/ELVs	$114 billion	$5400	2.7%
5	Plus more ELVs	$118 billion	$5600	3.1%
6	Or add Shuttle-C	$131 billion	$6300	2.9%
	Expanded civil demand			
7	Low rate ALS HLV	$128 billion	$4400	1.9%
8	ALS HLV and Shuttle-C	$142 billion	$4900	2.0%
	Expanded DoD demand			
9	High rate ALS HLV	$144 billion	$2100	2.2%
10	ALS HLV and Shuttle-C	$159 billion	$2300	2.2%

NOTE: Budget growth rates for launch vehicles and payloads

Constrained demand	–0.6 to 1.0% per year
Nominal demand	2.0 to 2.3% per year
Expanded civil demand	About 5% per year
Expanded DoD demand	About 8.8% per year

Evaluation criteria selected in Sec. 5.1 were developed further in discussion with space transportation planners and decisionmakers. For each demand level, applicable launch vehicle mixes were evaluated in terms of each evaluation criteria category:

- Performance: launch mix capacity and flexibility
- Cost: recurring and nonrecurring costs
- Operational risk: payload losses and delays
- Programmatic risk: development delays and overruns
- Mission requirements: requirements for specific missions

As discussed in Sec. 5.1.2, the analytic hierarchy process (AHP) was used in the selection of important criteria and the structuring of interviews with decisionmakers and planners. AHP-derived "figures of merit" were not used, however, to rank each launch vehicle mix. A more general technique of "stoplight" charts was used to rate each as most favorable, least favorable, or neutral in each evaluation category.

Some criteria were not significant discriminators for the assessed options, including, for example, environmental concerns and peak funding needs. Budgetary growth rates were significantly different for each level of demand examined, but not for launch vehicle options

applicable to a given demand level. These differences were due to the greater role played by payload costs, as compared to launch costs, for each demand. Finally, launch system resiliency was not as useful a discriminator as vehicle reliability and average standdown times because of problems with applying resiliency, which can be calculated for individual vehicles, to mixes of multiple types of vehicles. Appendix D provides a more extensive treatment of resiliency calculations.

Figure 6.1 shows the launch vehicle options for the case of constrained demand, considered from interviews the second most likely demand level. While the capacity of each option is approximately the same, the STS/ELV option provides greater flexibility in terms of being able to perform both manned and unmanned missions. Using only unmanned ELVs would be the least expensive option; using only the shuttle the most expensive. However, ELVs are likely to still be less reliable than the shuttle and will suffer a greater degree of payload losses and delays. All of these launch vehicle options use existing vehicles, so programmatic risk concerns for new developments are not applicable. Finally, the mission requirements category notes that some manned missions could not be flown with ELVs whereas other missions are most appropriate on ELVs. Thus the continuation of a mixed fleet of shuttle and ELVs is preferred even for a very constrained demand level.

Figure 6.2 shows the launch vehicle options for the case of a nominal demand, considered from interviews the most likely demand level. The addition of Shuttle-C flights creates the greatest amount of capacity, while maintaining only the current levels of STS and ELV flights leaves some demand unmet. The Shuttle-C is also the most costly option, and it is unclear whether all of its capacity would be used. The addition of more ELVs provides the most flexibility, but at the risk of larger payload losses and delays. Since the Shuttle-C requires some new development, it carries more programmatic risks than options using only existing vehicles. The most difficult question is whether there are specific mission requirements for the Shuttle-C that would justify its development.

Figure 6.3 shows the launch vehicle options for the case of an expanded civil demand, considered the third most likely demand level. In addition to shuttle and ELV flights, this level of demand would require developing new vehicles. Options using just an ALS heavy-lift vehicle, or a combination of Shuttle-C and ALS flights, could provide similar levels of capability to meet the demand.

Developing both an ALS and Shuttle-C is the more expensive option, with comparable levels of operational risk in terms of payload losses and delays. Developing only the ALS is more risky than including a Shuttle-C since setbacks in the ALS program would leave some demand unmet. The Shuttle-C uses current technologies and familiar operations and thus could be an early alternative for heavy-lift missions.

Figure 6.4 shows the launch vehicle options in the case of an expanded DoD demand, considered the least likely demand level by those interviewed. The alternatives here are the same as for the expanded civil demand case and the comparisons are the same for each evaluation category. Again, developing the ALS HLV alone is more economical than also developing a Shuttle-C, provided the ALS is successful. The Shuttle-C could, however, provide an earlier heavy-lift capability should mission requirements dictate.

In the case of uncertainty over which demand level will occur, existing vehicles are likely to be maintained. It is less likely that new systems will be allowed to go to full-scale development without known requirements, raising the problem of what to do about the Shuttle-C and ALS study efforts now under way and what actions should be taken to decide their future. These issues are addressed in the next section.

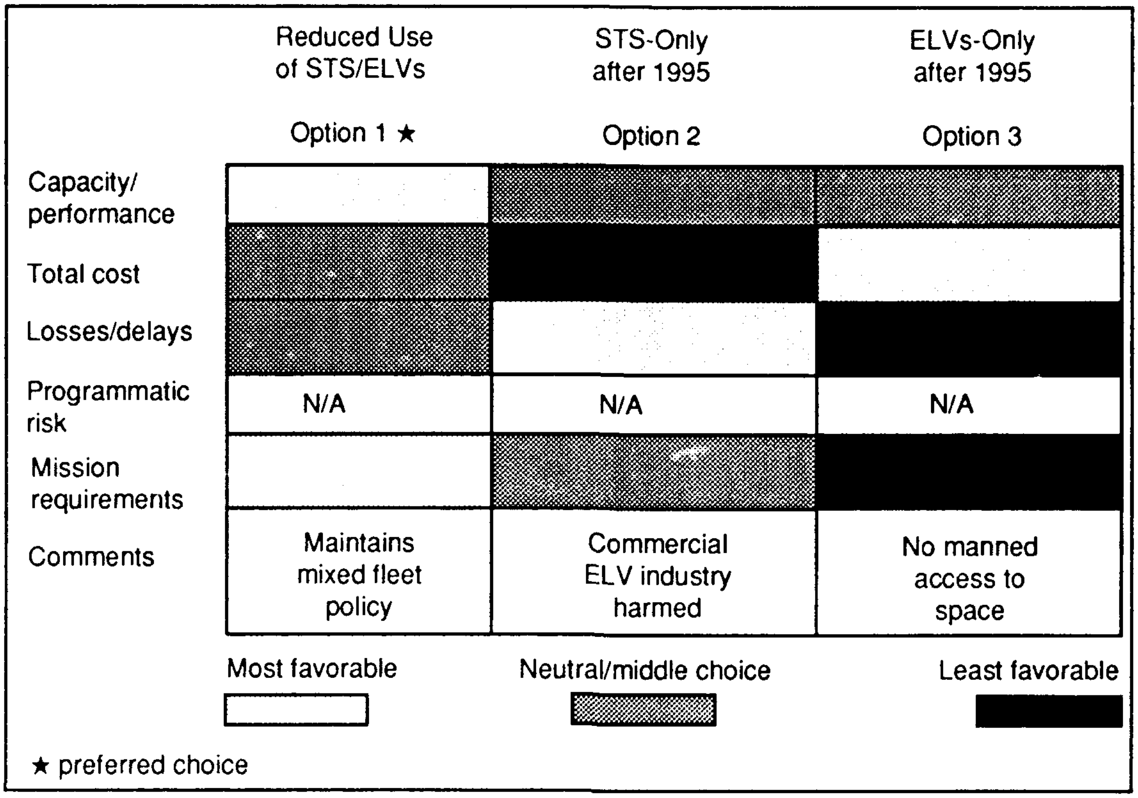


Fig. 6.1—Summary of launch vehicle options for a constrained demand

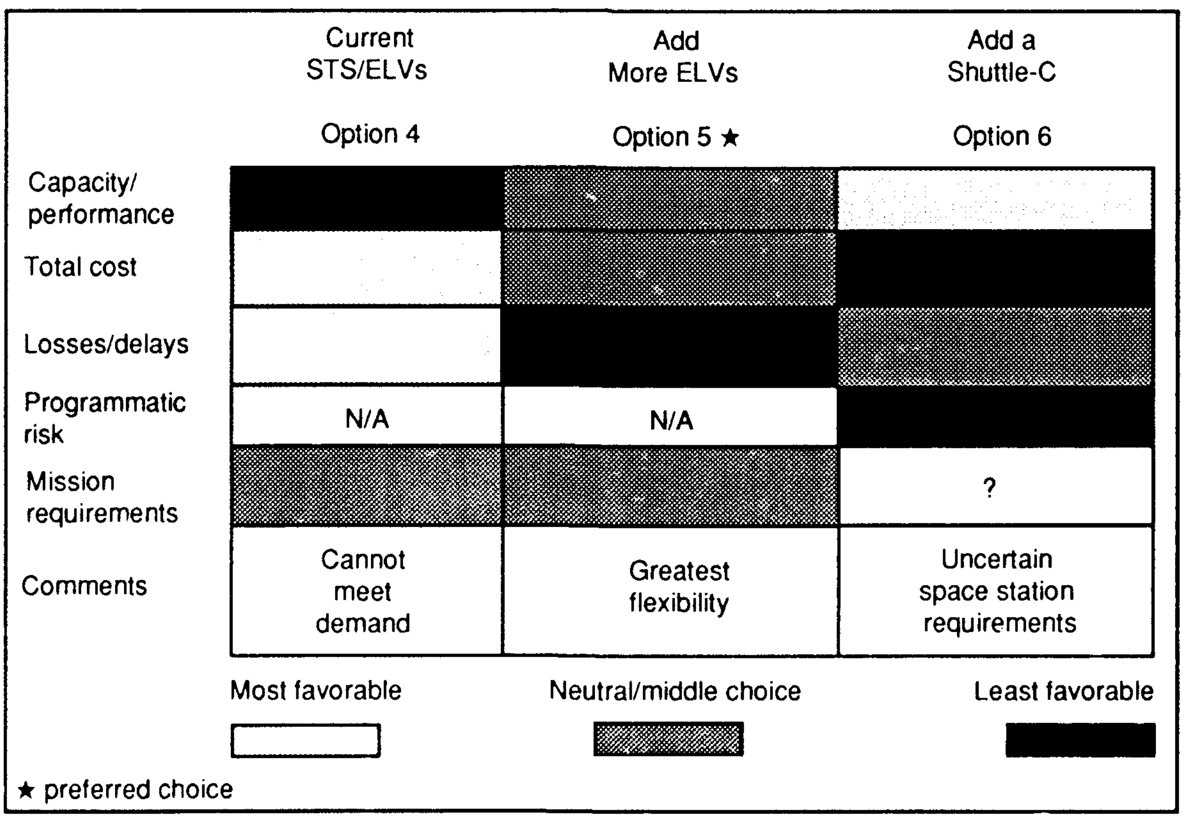


Fig. 6.2—Summary of launch vehicle options for a nominal demand

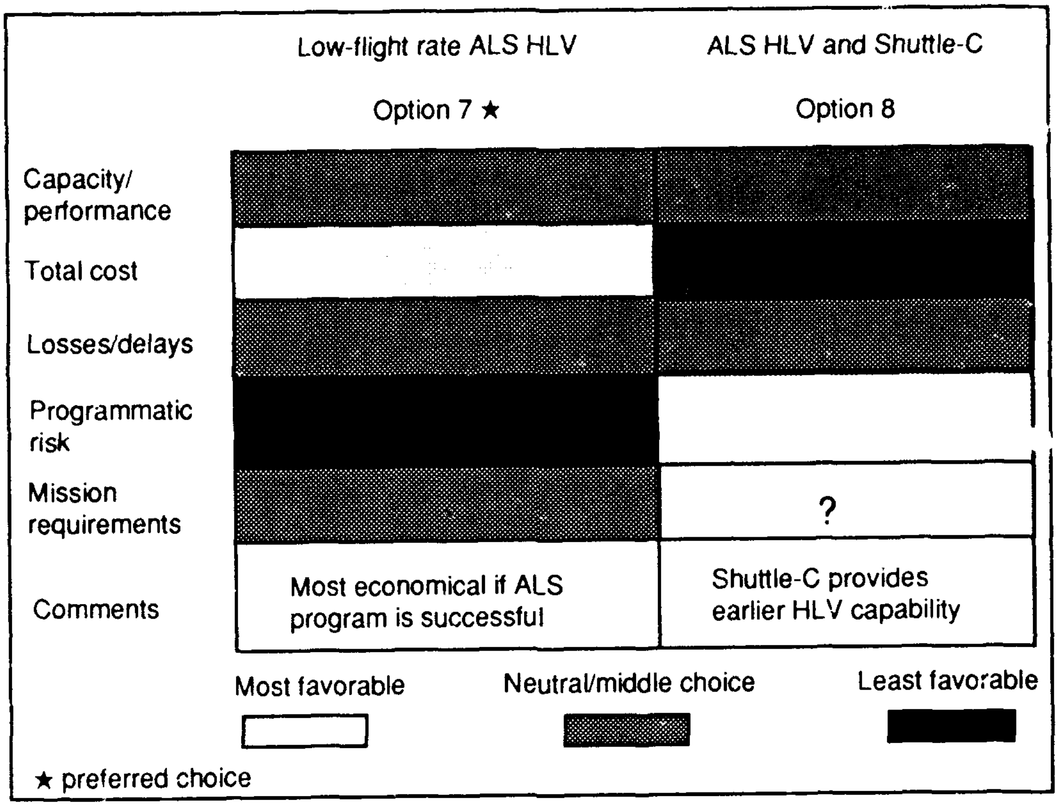


Fig. 6.3—Summary of launch vehicle options for an expanded civil demand

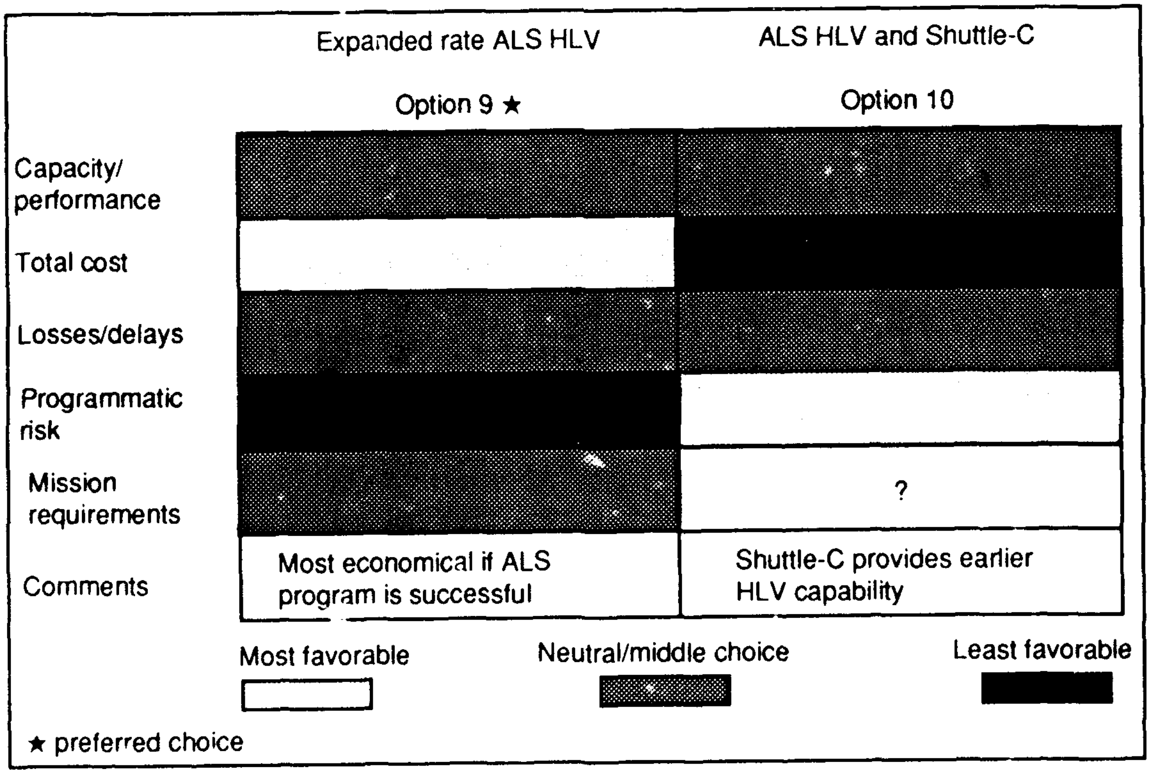


Fig. 6.4—Summary of launch vehicle options for an expanded DoD demand

VII. CONCLUSIONS AND RECOMMENDATIONS

7.1 OVERALL CONCLUSIONS

Table 6.2 summarized the key features of the launch vehicle mix alternatives discussed in Sec. IV. Based on those results and the interviews discussed in Sec. V, the conclusions fall into two groups: the first set assumes known demand levels, whereas the second assumes an uncertain demand. The events that could have the greatest influence on changing these conclusions are also discussed.

In the event of a *constrained demand level*, the preferred option would be to cut back on the number of both STS and ELV flights, but to maintain both capabilities. Whereas it might be argued that the "all-ELV" option is cheaper, the mix of STS and ELVs is preferred in maintaining a policy of manned access to space.

In the event of a *nominal demand level*, the preferred option would be for the United States to maintain current levels of STS and ELV procurements. Additional ELVs could be bought for temporary periods of increased demand, adding important flexibility. The diversity of STS and ELV mixes would ensure the United States had at least some access to space in the event of future accidents or standdowns. The Shuttle-C was rejected as being too expensive for routine transportation. It might be procured, however, if there was some special operational benefit, such as deploying space station elements, that would justify it on noncost grounds. As the space station deployment date slips, the Shuttle-C begins to come into competition with early ALS flights. In the nominal case, however, there is not yet an overlap of the two systems.

For the case of *expanded civil demand*, the preferred option for the United States is to retain current STS and ELV usage rates and add an ALS flying at a modest rate. The Shuttle-C is still too expensive to operate, save in the case of unique operational benefits. For the case of *expanded military demand*, an aggressive ALS effort would be required and again Shuttle-C would not play a role. The ALS would be added to current procurements of ELVs and shuttle flights. In both expanded demand options it is important to have lower costs and better operability (e.g., high reliability, shorter standdowns) over current launch vehicles. *If current payload costs continue, such operability concerns are as important, if not more so, than launch costs in their impact on total space system costs.*

In the event the United States is uncertain as to what demand level will transpire, shuttle and ELV flights should be procured as short-term demand levels dictate. *The ALS technology development should be supported until a decision is made on whether expanded demand levels will materialize.* Full-scale development of ALS vehicles will require expanded demand levels or major improvements in cost-effectiveness over current launch systems to justify its nonrecurring costs. Lacking expanded demand levels, ALS technologies might be incorporated in improving the operation of current ELVs. *The key issue for the case of uncertain demand is whether the United States needs a heavy-lift vehicle, and that decision can be delayed until the early 1990s.* A decision would be needed by 1992 for an aggressive ALS effort, and by 1993 for a modest rate ALS. At the constrained level, a heavy-lift vehicle is not likely to be needed.

The Shuttle-C was not cost-effective at expanded demand levels, and was not required at constrained demand levels. In the nominal demand case, however, the current space station schedule requires a decision on this vehicle. Proponents argue that a heavy-lift Shuttle-C would allow launching major station elements already assembled, thus lowering the number of flights required to deploy the station, lower the amount of on-orbit assembly times required, and free manned shuttle flights for other missions. Opponents argue that the

shuttle, with advanced solid-rocket motors, is capable of deploying the space station and a Shuttle-C is an unnecessary expense. A third alternative would be to develop new, high-performance ELVs such as a heavy-lift Titan V. This would involve major changes in the Titan 4 design, such as a larger center core stage and a transition to all-cryogenic fuels. The design is still immature, however, and no government commitment has been made concerning its potential development. Evaluating these alternative vehicles for the space station program was outside the scope of this study, but the vehicles were a major concern in several interviews with space transportation decisionmakers.

Major impacts to the above conclusions could result from decisions on the future of the shuttle program. In the time frame of this study, new shuttle orbiters were not required as a result of losses or "wear-out." Losing another orbiter may lead to the cancellation of the shuttle program, resulting in additional vehicles being required to make up the capacity shortfall. A withdrawal from manned space operations would likely signal a more constrained demand level as well.

At currently planned flight rates, the shuttle fleet will be wearing out about the year 2010 and replacement decisions will be needed about 10 years before then. One option is to refurbish the fleet over time, much as the United States has done with its B-52 bombers, or replacement Orbiters could be purchased. There could be a transition to a Shuttle II based on advanced rockets, as is under study at the NASA Langley Research Center.[1] The shuttle may also be replaced by higher risk technology, such as the scramjets being developed under the National Aerospace Plane program. A series of technical breakthroughs there might accelerate the replacement of the shuttle fleet. *Decisions on shuttle replacement should be made around the mid- to late-1990s, given the long lead times for modern aerospace vehicles and the possibility of faster orbiter wear-out.* The definition of shuttle replacements will depend on research results from several technology efforts, as well as shuttle operating experience. It is premature to say now how far research efforts will have progressed when a decision is required.

Other events which could alter the conclusions would be large drops in the operating costs of the Shuttle-C without a large rise in development expenses. This seems unlikely given the current known costs of shuttle hardware and operations. The Titan V may develop as a major alternative vehicle for heavy-lift missions, not just against the Shuttle-C, but in general if its costs drop and its reliability increases over that of historical Titan vehicles. Again, this seems unlikely as the new Titan would be essentially a new vehicle, although based on known technology. If the ALS program should suffer a major disruption or cancellation in a tight budgetary environment, it is likely that efforts to expand space traffic will be in political and fiscal trouble and the rationale for an ALS effort will fade.

Some analysts have argued that the commercial launch companies could introduce new, lower cost launch services.[2] Most of these companies are offering government-developed vehicles such as the Titan, Delta, and Atlas, albeit with more efficient ground operations and management. *Entirely new vehicles, such as the Industrial Launch Vehicle of the American Rocket Company or the Pegasus of Orbital Sciences Corporation are still too small to service a significant share of total demand.* Although still untested, they appear to have a good chance at sustaining themselves with new, small payloads such as "lightsats" and traditional sounding rocket/Scout-class experimental packages. Unfortunately, they are unlikely to play as large a role as conventional technology vehicles for at least the next decade because of their relatively small capacities.

The most important, but difficult to predict, factor is whether there will be any significant decrease in payload costs over the coming years. Lower payload costs affect the

[1]Craig Covault, "NASA Speeds Studies for 21st Century Successor to Today's Space Shuttle," *Aviation Week & Space Technology*, October 10, 1988, p. 50.

[2]James Bennett and Phillip Salin, "The Private Solution to the Space Transportation Crisis," *Space Policy*, August 1987, pp. 181–205.

required reliability of vehicles and help open budget wedges for developing transportation systems. It has been argued that more routine access to space, servicing, on-orbit checkout, gentler rides, more room in size and weight, etc. with new launch vehicles will help drive payload costs down. Similar claims were made for the effect of the shuttle on payload design, but it is claimed that events will turn out better this time.[3] Given that the vast majority of payloads are procured by and for the government, traditional private sector cost-reduction forces are not present. Payload costs may in fact come down only when larger numbers of commercial payloads are available to provide a measure for government efforts. This is a "chicken and egg" problem which is unlikely to be answered anytime soon.

To make rational decisions about space transportation, the United States needs to decide what it wants to accomplish in space, why, and whether it is willing to pay for the required efforts. In looking at the prospects for space activity, the safest prediction is that budgetary pressures will be high for the indefinite future. There will be increasing pressure not only to lower costs and improve effectiveness in launch vehicles, but to seek new sources of funds. Going beyond the federal budget could include new initiatives in international cooperation, such as buying foreign launchers and coproducing vehicles, and in the private sector, as in using market-driven technologies and operations. Many countries are interested in developing autonomous launch capabilities and many foreign companies have the capability to produce spacecraft. If the United States slows its development of space launch technology (whether publicly or privately), it is a safe prediction that others will take the lead with support from their governments.

7.2 CONCLUSIONS BASED ON INTERVIEW RESULTS

The conclusions in Sec. 7.1 above addressed several important questions in space transportation planning. The conclusions discussed next relate to the views of decisionmakers responsible for such planning. Turning technical and programmatic analyses to areas of disagreement and uncertainty (both technical and political) among decisionmakers can make space transportation choices clearer. A secondary goal of this study has thus been to identify areas of consensus and uncertainty in space transportation through interviews with a selection of those decisionmakers.

Proposing and debating the desirability of alternative strategies is most effective when participants share a consensus on the goals to be achieved. Even more so than debates over national security or economic policies, space policy lacks a consensus on its goals. Advocates of creating settlements on other planets are debating those favoring unmanned scientific exploration, as well as those who argue that most space activities are an unaffordable luxury. *The uncertainties confronting the United States result primarily from political indecision and the failure of the space policy community to forge a consensus on its goals; technical and programmatic uncertainties are of secondary importance.* This conclusion does not mean budgetary constraints and technical obstacles are not important, but that political uncertainty exacerbates already difficult choices. The Bush Administration should take steps to reduce this uncertainty by addressing space issues directly in both policy statements and budgetary priorities.

7.2.1 Areas of Consensus

The RAND interviews found a significant degree of consensus on broad policy issues exists among decisionmakers in space transportation planning. In each sector of space activity, there was agreement on key political questions. For the national security sector, few if any senior planners expected that space-based strategic defenses would be deployed in

[3]Maxwell W. Hunter, Wayne Miller, and Robert Gray, "The Space Shuttle will Cut Payload Costs," *Astronautics & Aeronautics*, June 1972, pp. 50–56.

the next 10 to 15 years. For the civil sector, it was expected that the United States would maintain a commitment to manned access to space—with or without the space station. For the commercial sector, all planners expected that the United States would seek to promote a commercial launch vehicle industry and maintain a mixed fleet of vehicles.

These areas of policy consensus are matched by a consensus on what the United States will likely do in the near term in its procurement of launch vehicles. This view results not so much from policy agreement, but from universal recognition of near-term budgetary pressures. Shuttle flights will continue, although possibly not at the levels that NASA is now projecting. The government will continue to buy expendable launch vehicles, or at least their services. This will continue until other alternatives become available such as an operational family of ALS vehicles. Even then, future upgrades of ELVs might themselves become the ALS family of vehicles. The view that both shuttle and ELV flights will continue for a wide range of demands was supported by the conclusions in Sec. 7.1 for each demand level. Other conclusions were not directly supported by the interviews, and these tended to be in the areas of uncertainty discussed below.

7.2.2 Areas of Uncertainty

Faced with budgetary tradeoffs, the Congress desires a broad, cooperative "master plan" from the civil and military space communities. Such a plan would enable the Congress to make informed judgments on how to efficiently meet U.S. space transportation requirements. Recognized obstacles to such a plan include uncertainty over future Administration policy and competition between NASA and the Department of Defense for leading roles. More importantly, and largely unrecognized, are obstacles due to internal differences within NASA and the Department of Defense. The NASA Office of Space Flight has yet to receive support from the NASA Office of the Space Station for the Shuttle-C proposal. The Department of Defense must consider not only interservice demands for space roles, but intercommand demands as well. The new Air Force Space Command seeks a role that at times conflicts with traditional roles performed by the Air Force Systems Command. In turn, both are wary of the United States Space Command which includes the Navy and Army Space Commands as well as that of the Air Force. Given the problems of reaching internal agreement, it is not surprising that the Department of Defense and NASA have yet to submit a "master plan" for space transportation.[4]

Congressional desires for integrated planning assume a degree of political agreement that just may not be possible. This lack of agreement places further burdens on the Executive Branch to make budgetary tradeoffs that the agencies are reluctant to do, and to define the U.S. role in space. The new National Space Council could certainly find itself with a full agenda if the new Administration seeks to resolve these issues there. Alternatively, budget pressures may provide the rationale for deferring their debate. Decisionmakers ask why they should suffer debate now when it might be put off, presumably to a time when more information is available.

As stated at the beginning of Sec. 7.1, the uncertainties facing space transportation planners are primarily political and their persistence makes rational planning, comparing means and ends, difficult. This difficulty creates significant financial, operational, and political costs to U.S. space transportation in maintaining excess capacity, continuing inefficient launch systems, or forgoing opportunities in space. Taking significant steps toward defining the U.S. role in space requires addressing the broad purposes of space transportation, which are summarized below.

[4]See App. G for a discussion of likely analytical problems and biases in producing a space transportation master plan for the Congress.

7.2.3 The Question of Purpose in Launch Vehicle Planning

The central theme that runs through both the internal debates and the external conflicts for each institutional group is the issue of *why launch vehicles are built*. One view might be labeled "reactive" in that it sees launch vehicles as being built only after approved payloads exist. Launch vehicles are nothing more than means to an end, a way of placing a particular object in space in the service of the national interest. Because payload development times are comparable to launch vehicle construction times, it is argued that the United States does not, and should not, need to build vehicles in anticipation of payloads. Budgetary pressures also provide incentives to eliminate any "surplus" launch vehicles that might provide an inventory cushion against unexpected demands.

An alternative view advanced by transportation planners in both the Department of Defense and NASA argues that launch vehicles shape the types of payloads launched and thus vehicles should be designed in anticipation of future needs. This "proactive" view is sometimes taken further in arguing that the creation of launch vehicles should be used as a tool to shape the traffic demand. ALS proponents argue that not only will their vehicles reduce launch costs, but more generous payload volumes will help lower the payload costs which dominate space system costs. NASP proponents argue that air-breathing, single-stage-to-orbit technologies will not only be cheaper than current rockets, but more frequent, reliable access to space will help lower payload costs as well by providing servicing and repair opportunities.

The "proactive" view argues that payload designers are conservative and design only for vehicles that exist or will soon exist. NASA's space station managers, for example, cite the need to plan conservatively in their reluctance to make the Shuttle-C a requirement for initial deployments. They also fear that associating Shuttle-C costs with the space station will harm support for a program that is of greater importance to NASA. Reluctance to require use of the Shuttle-C is sometimes less a matter of technical judgment than a political calculation of Congressional and Presidential support for the space station.

The "chicken or egg" debate over whether launch vehicles or payload requirements come first means different things to the Congress, DoD, and NASA. Congress is wary of building a vehicle without seeing specific associated payloads and sees its "reactive" view as a prudent guardian of the public purse. DoD supporters of a broader role for military space operations see "proactive" vehicles, such as ALS and NASP, as a means for gaining control of growing payload costs and enhancing the effectiveness of military missions. They see delay of such vehicles as shortsighted. This is countered with arguments that funding new launch vehicles raises difficult, near-term tradeoff questions for existing military satellite programs. In the case of NASA, it would like to develop the Shuttle-C as well as improve the shuttle program, but not at risk to space station support. Having potential launch vehicles jeopardize current programs is thus a problem common to both DoD and NASA.

The two policy-level questions which began this study (see Sec. 1.2) can be reexpressed in terms of the debate over the purpose of launch vehicles. How can the competing arguments of the proactive and reactive views be resolved in selecting and implementing space transportation plans? In particular, which launch vehicle decisions should be made now and which can be delayed? The next subsection addresses these questions with recommendations for U.S. space transportation planners and decisionmakers.

7.3 RECOMMENDATIONS FOR THE FUTURE

The shuttle and ELVs in a mixed fleet can and should provide the backbone of U.S. access to space in the next decade. Decisions to develop a heavy-lift vehicle should be deferred for

several years until their technical benefits become more compelling or until national needs (such as increased traffic demands) emerge for their adoption.

The Shuttle-C is not desirable for any of the baseline traffic demands. However, it may be justified if it sufficiently reduces the number of shuttle flights, assembly time, and associated costs and risks of the space station program. As an institution, NASA has not been able to definitively balance the potential technical benefits of the Shuttle-C with the political costs of further increases to the space station's budget. *An independent assessment of the Shuttle-C program should be conducted soon and a recommendation made to the Bush Administration on whether to proceed to full-scale development, depending on the schedule of the space station program.* This is the most pressing question for the near term as the vehicle's probable utility fades beyond the 1990s, assuming ALS technology developments proceed. Failure to fully evaluate the Shuttle-C for the space station program may result in unnecessary costs and risks to the station effort.

The United States should actively decide what it wishes to accomplish in space and create launch options rather than merely responding to military, scientific, and economic competitions. This is not meant to endorse the proactive view, but rather to favor making policy decisions which enable rational planning of space transportation. Lacking consensus on long-range demand levels, the United States should engage in evolutionary improvements in existing systems while supporting technology research in new launch systems. *ALS technology efforts should be supported while incremental improvements are made in the capabilities of the shuttle and ELV fleets. The technical and cost benefits of the ALS program are not yet sufficient to justify a commitment to a new full-scale development program.* Without major increases in space traffic demand, the United States should create a new launch vehicle line only when quantum improvements in cost-effectiveness and/or new capabilities become available. Technology programs are less costly than development programs and can be continued more easily during periods of budgetary stringency. Their importance lies in providing options for transitioning to development programs as economic and technical opportunities become available.[5]

The claims of the proactive school on the effects of launch vehicles on payloads do not have to be accepted *in toto* to see the benefits of future launch systems. Similarly, the concerns of the reactive school should not be taken so literally that opportunities are missed due to a lack of vision on how to exploit new capabilities. *The key is to require a clear separation between operations-oriented and research-oriented launch vehicle programs, and a political commitment to space access without specific payloads in hand.*

This recommendation places bounds on the range of debate for the proactive and reactive viewpoints. Research programs attempting to advance launch technology, such as the ALS and NASP, need to avoid raising expectations so high that their goals are confused with the operational realities of existing programs. For example, research programs should not commit to initial operating capability (IOC) dates for potential vehicles since payload designers cannot be sure that those objectives will be met.[6] A commitment to space access is required, however, to sustain the research programs which create new capabilities and improvements to current systems. Lack of such a commitment continues the uncertainties which have beset space transportation planning, to the detriment of the U.S. role in space.

[5]Michael Rich and Edmund Dews with C. L. Batten, Jr., *Improving the Military Acquisition Process—Lessons from RAND Research*, The RAND Corporation, R-3373-AF/RC, February 1986.

[6]Slips in the first flight of the shuttle, over several years, caused disruptions to payloads which had been scheduled to fly and which did not have backup vehicles.

Appendix A
PROJECTIONS OF U.S. SPACE TRANSPORTATION DEMAND

This appendix documents a review of space transportation demand projections through the year 2010. The work was done as part of the assessment of space traffic ranges the U.S. government might be called upon to meet for the 1988–2010 period.

A.1 HAZARDS OF ESTIMATING LAUNCH DEMAND

Historically, projections of space traffic demand have been subject to a variety of uncertainties. One set of uncertainties relates to space traffic demand itself, which is a function of political and budgetary decisions as to what the United States seeks to accomplish in space. The second set of uncertainties relates to the actual timing of space launches, which is affected by budgetary constraints, technical failures, and changes in mission requirements.

Figure A.1 shows NASA forecasts of launch activity in 1988 as a function of the year of the forecast.[1] Of course, none of the forecasts included the possibility of a catastrophic accident in 1986, which led to the actual 1988 figure of one shuttle flight. The lack of fleet downtimes is just one of the hazards of translating an estimated traffic demand into flight rate plans.

A contributing factor to uncertainty in launch activities has been the frequent underestimation of technical, market, and budgetary constraints to high flight rates by prospective payload users. The vast bulk of U.S.-launched payloads are government owned and operated. Government payload sponsors have incentives to overestimate their own needs in the continuing struggle for the federal budget. In the case of NASA, Congress has regularly appropriated a lower amount of money than that assumed by NASA's advanced planning staffs. In seeking assurance that national security missions will be performed, there is a tendency to underestimate military satellite lifetimes, thus leading to higher replacement rate projections.[2] Commercial organizations also have incentives to overestimate flight rates, if only to support optimistic market forecasts for their services or products. Finally, technical organizations as a whole are often optimistic on construction costs and schedules. However, conservative design practices lead to longer satellite lifetimes, further lowering actual launch requirements.

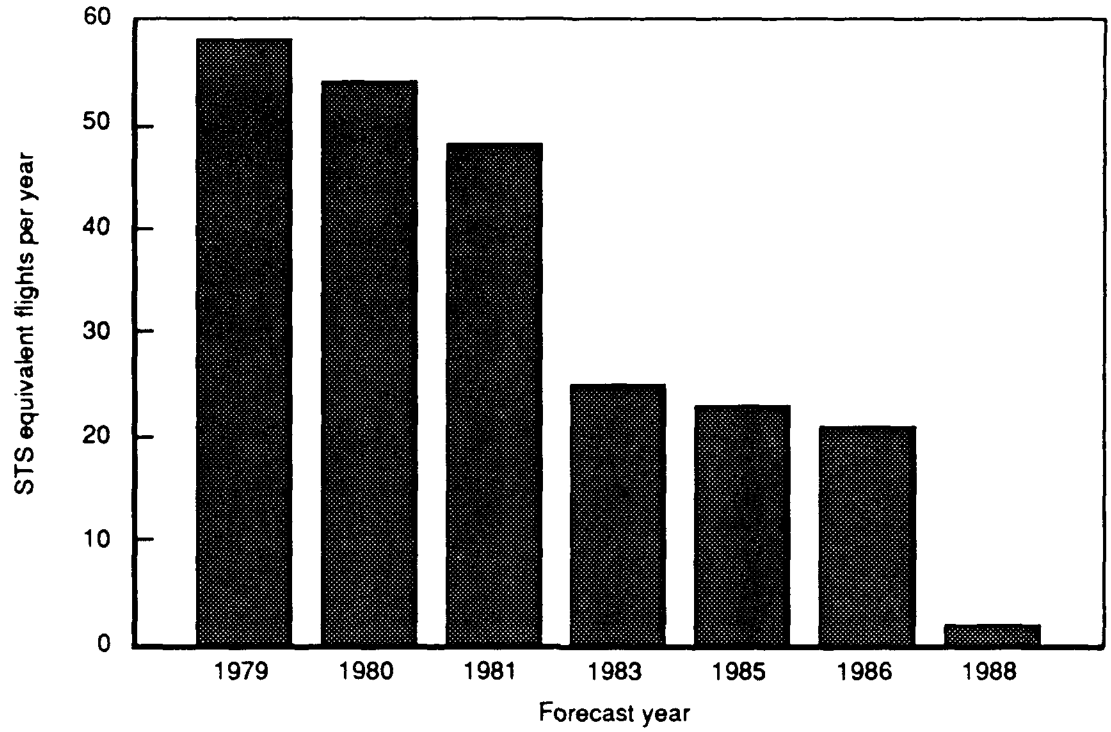
To assess the credibility of various projections of future space traffic, both civil and military, future projections were compared with historical data. Furthermore, a range of traffic levels were examined to bound the range of potential demand and to cover various future scenarios (e.g., deployment of strategic defenses in space).

A.2 STANDARDIZING THE TRAFFIC RATES

Space traffic consists of a wide variety of payloads going to many different locations. Figure A.2 is a simplified overview of the primary destinations of military payloads in Earth orbit. Satellites with similar functions tend to share the same orbits. For example, communications satellites are found in geosynchronous orbits (GEO), navigation satellites in mid-altitude, mid-inclination orbits, and weather satellites in polar orbits.

[1]Congressional Budget Office, *Setting Space Transportation Policy for the 1990s*, U.S. Government Printing Office, Washington, D.C., October 1986, p. 11.

[2]General Accounting Office, *Satellite Acquisition: Global Positioning System Acquisition After Challenger's Accident*, GAO/NSIAD-87-209BR, U.S. Government Printing Office, Washington, D.C., September 1987, p. 29.



SOURCES: Congressional Budget Office, NASA.

Fig. A.1—NASA forecasts of annual launch activity for 1988

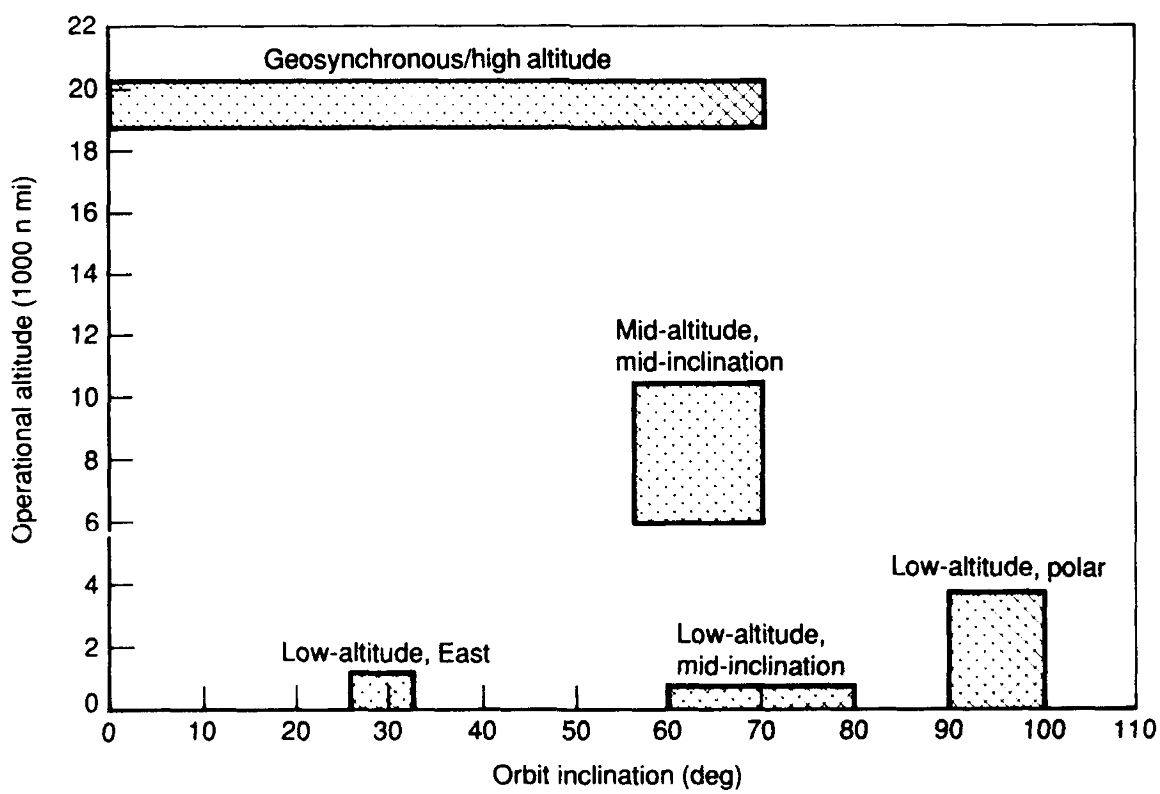


Fig. A.2—Space traffic regions

Launching due east out of Cape Kennedy (a 28.5 deg inclination) would place a payload in a low inclination, usually low altitude, orbit. This is a common first destination for many civil and military payloads, which are then moved to their final locations using upper stages or orbital transfer vehicles. Because inclination plane changes are more energy-expensive than altitude changes, every attempt is made to minimize them. Thus, polar orbit satellites are launched directly into polar orbits, rather than attempting "dog-leg" turns from lower inclination orbits.

A common method for comparing different payloads and launchers is to reduce them all to either pounds placed in a shuttle orbit (e.g., 28.5 deg at 100 n mi) or equivalent STS flights. Payload weights going to LEO can be counted directly. Payloads going beyond LEO must count not only their own masses, but the masses of their upper stages and airborne support equipment (ASE). Payloads flown or to be flown each year are then added up to get a measure of pounds per year to a "LEO equivalent" orbit.

Alternatively, launch vehicles flown each year can be counted and assigned an "STS equivalence" such as .25 for a McDonnell-Douglas Delta or 5.0 for a Saturn V. This convention encompasses not just differences in payload capacity to a standard orbit, but also judgments as to the number of vehicles required to perform the same mission. For example, a shuttle could launch four Navstar satellites compared to one on a Delta, thus giving the Delta a value of .25. Calculations using the payload capacity of a specific vehicle configuration can give different results. If the Delta 7925's 11,110 lb capacity to LEO is divided by the shuttle's 55,500 lb nominal capacity, the equivalence is only .20.[3] This difference occurs because the shuttle does not usually fly fully loaded (so its capacity is not fully used), and only four payload bay locations are available for the PAM-D upper stages used by Navstar satellites, thus more satellites could not be accommodated in any event. The shuttle itself has an equivalence factor of 1.0.

The need to consider where a payload will be deployed, as well as what vehicle will carry it into orbit, can be a severe complicating factor in the use of the STS equivalence convention. Its major benefit is that if done carefully and explicitly, it provides a measure of launch effort over time that is related to an easily grasped image—a shuttle launch.

A.3 U.S. SPACE EFFORTS, 1958–1987

A first application of the standardizing methods noted above was made in examining historical records of U.S. launch activity from 1958–1987.[4] The purpose of this effort was to see how U.S. space activity has fared over time while using a broad measure such as STS equivalent flights. This was preferable to simply counting payloads or launchers (which come in many sizes) or measuring pounds to LEO (which is difficult to extract from available records).

The data for the effort came from assigning STS equivalent factors to the historical record compiled at the Congressional Research Service by Charles Sheldon for 1958–1980, with data from later years coming from the annual *Aeronautics and Space Report of the President* and TRW Corporation's annual *Space Log*.[5] Data tabulations are attached as Table A.1. A summary of STS equivalent factors for historical expendable launch vehicles is attached as Table A.2. For current ELVs, equivalent STS factors would be:

[3]"McDonnell Plans Rapid Buildup of Delta Launcher Fleet," *Aviation Week & Space Technology*, February 16, 1987, p. 114; and McDonnell-Douglas, "Delta II—The Next Generation," corporate brochure, Huntington Beach, CA, February 1988.

[4]This was based on earlier work performed while the author was at Rockwell International.

[5]See U.S. Congress, *United States Civilian Space Programs 1958–1978*, Vol. 1, House Subcommittee on Space Science and Applications, January 1981; Office of Science and Technology Policy, *Aeronautics and Space Report of the President*, App. D, Executive Office of the President, Washington, D.C., U.S. Government Printing Office, 1981–1985; and TRW, *Space Log 1984–1985*, Redondo Beach, CA, 1986.

ELV	STS Equivalence
Scout	0
Delta	.25
Titan 2	.3
Titan IIIB	.4
Atlas Centaur	.5
Titan 34D	.75
Titan 4	.75

Figure A.3 is a summary of U.S. launch attempts since 1957. The pace of launches has dropped since the peak of the Apollo years. Beginning with the first shuttle flight in 1981, there was an increase in launches per year, which declined as expendable launch vehicles were phased out. Finally, note the sharp drop in 1986 with the loss of the Challenger and several ELVs that year.

Figure A.4 portrays the same information as Fig. A.3, converted into STS equivalent flights. Here the decrease in activity with the STS 51-L and ELV accidents is even more dramatic. For the sake of comparison, a rough "pounds to orbit" scale is shown. During the peak of Apollo, the United States was placing upwards of 2 million lb per year into LEO equivalent orbit. Since the end of Skylab, however, U.S. launches have averaged less than 800,000 lb per year.

A.4 U.S. MANIFESTED FLIGHTS 1988–1995

In the wake of the 1986 accidents, considerable effort has gone into restructuring both the shuttle and ELV programs. In March 1988, NASA published its first complete manifest of future activity since the Challenger accident.[6] The Department of Defense published its own manifest at the same time, but reports of its general contents had already appeared in the aerospace press.[7] Both manifests covered the period from 1988 to 1995, and should constitute a reliable picture of near-term U.S. activity as both payloads and vehicles are identified.[8] It should be kept in mind that these manifests include the payload backlog resulting from the standdowns of several ELVs and the shuttle.

Table A.3 is a tabulation of the DoD/NASA manifest data for 1988–1995. It shows both total launches planned per year and total effort in STS equivalent flights. The manifest count of total ELVs used by the Department of Defense through 1995 corresponds closely to the number of announced vehicle buys. The number of Titan 34D vehicles, however, was derived from noting the gap between planned DoD flights and known purchased vehicles. This may represent an overestimation of DoD activity.

Figure A.5 is a summary pictorial of the data in Table A.3. It shows the DoD reliance on ELVs and the NASA reliance on the shuttle. This situation is the result of many changes over the past five years. Although a national policy decision was made in the 1970s to transition all payloads to the shuttle, the DoD resisted through reluctance to depend on one launch system, especially one not under its direct control. Figure A.6 shows the distribution

[6]Office of Space Flight, *Payload Flight Assignments—NASA Mixed Fleet*, NASA Headquarters, Washington, D.C., March 1988.

[7]"Military Launcher Program Meeting Critical Milestones," *Aviation Week & Space Technology*, February 1, 1988, pp. 36–38.

[8]The DoD manifest shows only launch vehicles by year at the unclassified level.

Table A.1

U.S. HISTORICAL LAUNCH RECORD

	A	B	C	D	E	F	G	H
1	References:	Rockwell IL AE-SA-83-009		AE-111-85-009				
2		1958-1980 uses Sheldon Master list			1981-85 uses TRW Log. Aeronautics and Space Report			
3	Attempted Launches						STS Equivalent Flights	
4				Historical Levels of U.S. Space Efforts			1958-1987	
5								
6	Year	Vehicle		No. Launched	STS Equiv.	STS subtotal		
7		Jupiter C		6	0.05	0.3		
8		Vanguard		6	0.05	0.3		
9		Thor-Able		3	0.1	0.3		
10		Juno II		1	0.1	0.1		
11		Atlas B		1	0.1	0.1		
12	1958			17		1.1		
13								
14		Thor-Agena A		9	0.1	0.9		
15		Thor-Able III		2	0.1	0.2		
16		Atlas-Able IV		2	0.2	0.4		
17		Juno II		4	0.1	0.4		
18		Vanguard		4	0.05	0.2		
19	1959			21		2.1		
20		Thor-Agena A		8	0.1	0.8		
21		Thor-Agena B		3	0.1	0.3		
22		Thor-Able IV		1	0.2	0.2		
23		Thor-Delta		3	0.1	0.3		
24		Thor-Able Star		6	0.1	0.6		
25		Atlas Able V		2	0.3	0.6		
26		Atlas Agena A		3	0.3	0.9		
27		Juno II		2	0.1	0.2		
28		Scout		1	0	0		
29	1960			29		3.9		
30		Thor-Agena A		9	0.1	0.9		
31		Thor-Agena B		17	0.1	1.7		
32		Thor-Able Star		3	0.1	0.3		
33		Thor-Delta		4	0.1	0.4		
34		Atlas D		3	0.2	0.6		
35		Juno II		3	0.1	0.3		
36		Scout		5	0	0		
37	1961			44		4.2		
38		Thor-Agena B		17	0.1	1.7		
39		Thor-Agena D		7	0.1	0.7		
40		Thor-Able Star		3	0.1	0.3		
41		Thor-Delta		9	0.1	0.9		
42		Atlas Agena B		15	0.3	4.5		
43		Atlas D		3	0.3	0.9		
44		Scout		5	0	0		
45	1962			59		9		
46		Thor-Agena D		9	0.15	1.35		
47		TAT Agena D, B		11	0.25	2.75		
48		Atlas Agena B, D		8	0.4	3.2		
49		Thor-Delta		7	0.15	1.05		
50		Thor-Able Star		2	0.1	0.2		
51		Atlas Centaur		1	0.4	0.4		
52		Atlas D		1	0.3	0.3		
53		Scout		9	0	0		
54	1963			48		9.25		
55		Thor-Agena B		2	0.15	0.3		
56		Thor-Agena D		3	0.15	0.45		
57		Thor-Delta		4	0.15	0.6		
58		Thor-Able Star		3	0.1	0.3		
59		TA Delta		1	0.2	0.2		
60		Atals Agena B		3	0.4	1.2		
61		Atlas Agena D		13	0.4	5.2		

Table A.1—(continued)

	A	B	C	D	E	F	G	H
62		Atlas Centaur		2	0.4	0.8		
63		TAT Agena D		18	0.25	4.5		
64		Titan II		1	0.4	0.4		
65		Titan IIIA		2	0.4	0.8		
66		Scout		9	0	0		
67		Saturn I		3	1	3		
68	1964			64		17.75		
69		Thor-Agena B		1	0.2	0.2		
70		Thor-Agena D		2	0.2	0.4		
71		Thor-Able Star		3	0.1	0.3		
72		Thor-FW4		2	0.15	0.3		
73		Thor-Altair		2	0.15	0.3		
74		Thor-Delta		5	0.15	0.75		
75		TA Delta		3	0.2	0.6		
76		TAT Agena D		17	0.25	4.25		
77		Atlas Agena D		12	0.4	4.8		
78		Atlas Satar		3	0.	0.9		
79		Atlas Centaur		2	0.4	0.8		
80		Titan IIIA		2	0.4	0.8		
81		Titan IIIC		3	0.75	2.25		
82		Titan II		5	0.4	2		
83		Saturn I		3	1	3		
84		Scout		5	0	0		
85	1965			70		21.65		
86		Thor-Agena D		2	0.2	0.4		
87		Thor-Burner II		1	0.2	0.2		
88		Thor-Delta		2	0.15	0.3		
89		Thor-FW4		2	0.15	0.3		
90		TAT Agena D		10	0.3	3		
91		TAT Agena B		1	0.3	0.3		
92		Atlas D		1	0.3	0.3		
93		Atlas Agena B		1	0.4	0.4		
94		Atlas Agena D		24	0.5	12		
95		Atlas Satar		3	0.3	0.9		
96		Atlas Centaur		4	0.5	2		
97		Titan II		5	0.4	2		
98		Titan IIIB-Agena D		3	0.5	1.5		
99		Titan IIIC		3	0.75	2.25		
100		TA Delta		6	0.15	0.9		
101		Saturn IB		1	2	2		
102		Scout		9	0	0		
103	1966			77		28.75		
104		Thor-Agena D		7	0.2	1.4		
105		Thor-Burner II		4	0.2	0.8		
106		Thor-Delta		2	0.2	0.4		
107		TA Delta		10	0.2	2		
108		TAT Agena D		5	0.3	1.5		
109		Atlas Agena D		9	0.5	4.5		
110		Atlas Satar		1	0.3	0.3		
111		Atlas Centaur		4	0.5	2		
112		Titan IIIC		3	0.75	2.25		
113		Titan IIIB-Agena D		7	0.5	3.5		
114		Saturn V		1	0.5	0.5		
115		Scout		7	0	0		
116	1967			60		19.15		
117		Thor-Delta		2	0.2	0.4		
118		Thor-Burner II		2	0.2	0.4		
119		Thor-Agena D		10	0.2	2		
120		TAT Agena D		1	0.3	0.3		
121		TA Delta		6	0.2	1.2		
122		Atlas Burner II		1	0.3	0.3		

Table A.1—(continued)

	A	B	C	D	E	F	G	H
123		Atlas Agena D		2	0.5	1		
124		Atlas F-Satar		2	0.3	0.6		
125		Atlas Centaur		3	0.5	1.5		
126		Titan IIIC		2	0.75	1.5		
127		Titan IIIB-Agena D		8	0.5	4		
128		Saturn IB		2	2	4		
129		Saturn V		2	5	10		
130		Scout		5	0	0		
131	1968			48		27.2		
132		Thor-Delta		8	0.2	1.6		
133		TA Delta		3	0.2	0.6		
134		Thor-Burner II		1	0.2	0.2		
135		Thor-Agena D		10	0.2	2		
136		Atlas Satar		1	0.3	0.3		
137		Atlas Agena D		1	0.5	0.5		
138		Atlas Centaur		3	0.5	1.5		
139		Titan IIIC		2	0.75	1.5		
140		Titan IIIB-Agena D		6	0.5	3		
141		Saturn V		4	5	20		
142		Scout		2	0	0		
143	1969			41		31.2		
144		Thor-Delta		6	0.2	1.2		
145		Thor-Agena D		7	0.2	1.4		
146		Thor-Burner II		2	0.2	0.4		
147		TA Delta		1	0.2	0.2		
148		Atlas Agena D		2	0.5	1		
149		Atlas Centaur		1	0.5	0.5		
150		Titan IIIC		2	0.75	1.5		
151		Titan IIIB-Agena D		5	0.5	2.5		
152		Saturn V		1	5	5		
153		Scout		3	0	0		
154	1970			30		13.7		
155		Thor-Delta		4	0.2	0.8		
156		Thor-Agena D		6	0.2	1.2		
157		Thor-Burner II		3	0.2	0.6		
158		TA Delta		1	0.2	0.2		
159		Atlas Satar		1	0.3	0.3		
160		Atlas Agena D		1	0.5	0.5		
161		Atlas Centaur		4	0.5	2		
162		Titan IIIC		2	0.75	1.5		
163		Titan IIID		1	0.75	0.75		
164		Titan IIIB-Agena D		5	0.5	2.5		
165		Saturn V		2	5	10		
166		Scout		4	0	0		
167	1971			34		20.35		
168		Thor-Delta		7	0.2	1.4		
169		Thor-Burner II		2	0.2	0.4		
170		Thor-Agena D		2	0.2	0.4		
171		Atlas Agena D		1	0.5	0.5		
172		Atlas Burner II		1	0.3	0.3		
173		Atlas Centaur		4	0.5	2		
174		Titan III		3	0.4	1.2		
175		Titan IIIC		1	0.75	0.75		
176		Titan IIIB-Agena D		5	0.5	2.5		
177		Saturn V		2	5	10		
178		Scout		5	0	0		
179	1972			33		19.45		
180		Thor-Delta		6	0.2	1.2		
181		Thor-Burner II		1	0.2	0.2		
182		Atlas Agena D		1	0.5	0.5		
183		Atlas Centaur		3	0.5	1.5		

Table A.1—(continued)

	A	B	C	D	E	F	G	H
184		Titan IIID		3	0.75	2.25		
185		Titan IIIC		2	0.75	1.5		
186		Titan IIIB-Agena D		4	0.5	2		
187		Saturn V		1	5	5		
188		Saturn IB		3	2	6		
189		Scout		1	0	0		
190	1973			25		20.15		
191		Thor-Delta		7	0.2	1.4		
192		Thor-Burner II		2	0.2	0.4		
193		Atlas D TEM-364		1	0.25	0.25		
194		Atlas Centaur		1	0.5	0.5		
195		Titan IIIC		1	0.75	0.75		
196		Titan IIID		2	0.75	1.5		
197		Titan IIIB-Agena D		3	0.5	1.5		
198		Titan IIIE-Centaur		2	0.85	1.7		
199		Scout		4	0	0		
200	1974			23		8		
201		Thor-Delta		12	0.2	2.4		
202		Thor Burner II		1	0.2	0.2		
203		Atlas Centaur		3	0.5	1.5		
204		Atlas F		1	0.25	0.25		
205		Atlas Agena D		1	0.5	0.5		
206		Titan IIID		2	0.75	1.5		
207		Titan IIIE-Centaur		2	0.85	1.7		
208		Titan IIIB-Agena D		3	0.5	1.5		
209		Titan IIIC		2	0.75	1.5		
210		Saturn IB		1	2	2		
211		Scout		3	0	0		
212	1975			31		13.05		
213		Thor-Delta		9	0.25	2.25		
214		Thor-Burner II		1	0.2	0.2		
215		Thor-TEM-364		1	0.2	0.2		
216		Atlas F TEM-364		1	0.25	0.25		
217		Atlas Centaur		3	0.5	1.5		
218		Titan IIID		2	0.75	1.5		
219		Titan IIIC		2	0.75	1.5		
220		Titan IIIB-Agena D		4	0.5	2		
221		Titan IIIE-Centaur		1	0.85	0.85		
222		Scout		3	0	0		
223	1976			27		10.25		
224		Thor-Delta		10	0.25	2.5		
225		Thor-TEM-364		1	0.2	0.2		
226		Atlas Agena D		2	0.5	1		
227		Atlas Centaur		3	0.5	1.5		
228		Atlas F-TEM-364		2	0.25	0.5		
229		Titan IIID		1	0.75	0.75		
230		Titan IIIE-Centaur		2	0.85	1.7		
231		Titan IIIC		2	0.75	1.5		
232		Titan IIIB-Agena D		2	0.5	1		
233		Scout		1	0	0		
234	1977			26		10.65		
235		Thor-Delta		10	0.25	2.5		
236		Thor-TEM-364		1	0.2	0.2		
237		Atlas Agena D		2	0.5	1		
238		Atlas F TEM-364		5	0.25	1.25		
239		Atlas Centaur		7	0.5	3.5		
240		Titan IIIC		3	0.75	2.25		
241		Titan IIID		2	0.75	1.5		
242		Titan IIIB-Agena D		2	0.5	1		
243		Scout		1	0	0		
244	1978			33		13.2		

Table A.1—(continued)

	A	B	C	D	E	F	G	H
245		Thor-Delta		3	0.25	0.75		
246		Thor-TEM-364		1	0.2	0.2		
247		Atlas F TEM-364		2	0.2	0.4		
248		Atlas Centaur		2	0.5	1		
249		Titan IIIC		3	0.75	2.25		
250		Titan IIID		1	0.75	0.75		
251		Titan IIIB-Agena D		1	0.6	0.6		
252		Scout		3	0	0		
253	1979			16		5.95		
254		Thor-Delta		1	0.25	0.25		
255		Thor TEM-364		1	0.2	0.2		
256		TA Delta		2	0.25	0.5		
257		Atlas F TEM-364		4	0.2	0.8		
258		Atlas Centaur		3	0.5	1.5		
259		Titan IIIB		1	0.4	0.4		
260		Titan IIID		2	0.75	1.5		
261	1980			14		5.15		
262		Thor-Delta		5	0.25	1.25		
263		Atlas F		2	0.3	0.6		
264		Atlas Centaur		4	0.5	2		
265		Titan III		1	0.4	0.4		
266		Titan IIIB-Agena D		2	0.5	1		
267		Titan IIIC		1	0.75	0.75		
268		Titan IIID		1	0.75	0.75		
269		Scout		1	0	0		
270		STS		2	1	2		
271	1981			19		8.75		
272		STS		3	1	3		
273		Delta		7	0.25	1.75		
274		Atlas Centaur		2	0.5	1		
275		Titan III		1	0.4	0.4		
276		Titan IIIC		1	0.75	0.75		
277		Titan IIID		3	0.75	2.25		
278		Atlas E		1	0.3	0.3		
279		Scout		0	0	0		
280	1982			18		9.45		
281		STS		4	1	4		
282		Delta		8	0.25	2		
283		Atlas-Centaur		2	0.5	1		
284		Atlas H,E		5	0.3	1.5		
285		Titan IIIB		2	0.4	0.8		
286		Titan 34D		1	0.75	0.75		
287		Scout		1	0	0		
288	1983			23		10.05		
289		STS		5	1	5		
290		Delta		4	0.25	1		
291		Atlas E		4	0.3	1.2		
292		Atlas Centaur		1	0.5	0.5		
293		Titan IIIB		2	0.4	0.8		
294		Titan 34D		5	0.75	3.75		
295		Scout		1	0	0		
296	1984			22		12.25		
297		STS		9	1	9		
298		Atlas E		2	0.3	0.6		
299		Atlas Centaur		3	0.5	1.5		
300		Titan IIIB		2	0.4	0.8		
301		Scout		2	0	0		
302	1985			18		11.9		
303		STS		2	1	2		
304		Scout		1	0	0		
305		Delta		2	0.25	0.5		

Table A.1—(continued)

	A	B	C	D	E	F	G	H
306		Atlas Centaur		1	0.5	0.5		
307		Atlas H.E		2	0.3	0.6		
308	1986			8		3.6		
309		STS		0	1	0		
310		Scout		1	0	0		
311		Delta		2	0.25	0.5		
312		Atlas Centaur		1	0.5	0.5		
313		Titan 34B		1	0.4	0.4		
314		Titan 34D		2	0.75	1.5		
315	1987			7		2.9		

Table A.2

STS EQUIVALENT VALUE OF ELVs

Titan Category	STS Equivalent
Titan III	.40
Titan III B	.40
Titan III C	.75
Titan III D	.75
Titan III B-Agena D	.05
Titan III E-Centaur	.85
Titan III A	.40
Titan II	.40
Saturn Category	
Saturn V	5
Saturn 1B	2
Saturn 1	1
Random Category	
Jupiter C	~0.05
Vanguard	~0.05
Juno II	~.1
Scout	0
Thor Category	
Thor Delta	.20– .1
TA Delta	.25– .1
Thor TEM 364	.25– .1
Thor Burner II	.25– .1
THor Agena D	.2
TAT Agena D	.3
Thor Agena B, A	.2 – .1
Thor Able Star	.1
Thor FW4	.2 – .1
Thor Altair	.2 – .1
Thor Agena A	.2 – .1
Thor Able III	.2 – .1
Thor Able	.2 – .1
Atlas Category	
Atlas Able IV	.3
Atlas Able V	.3
Atlas Agena A	.4
Atlas Agena B	.4
Atlas Agena D	.5
Atlas B	.3 – .2
Atlas D	.3 – .2
Atlas Centaur	.5 – .4
Atlas Satar	.3
Atlas F-Satar	.3
Atlas Burner II	.3
Atlas F TEM 364	.25

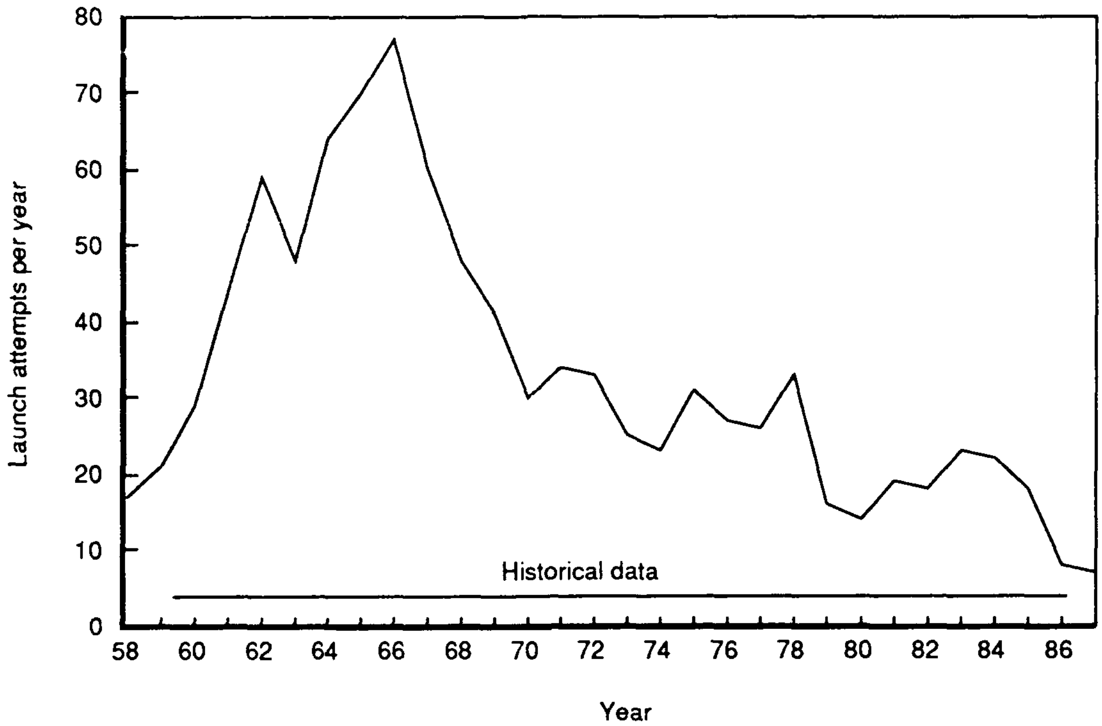


Fig. A.3—U.S. space efforts 1958–1987 (launch attempts)

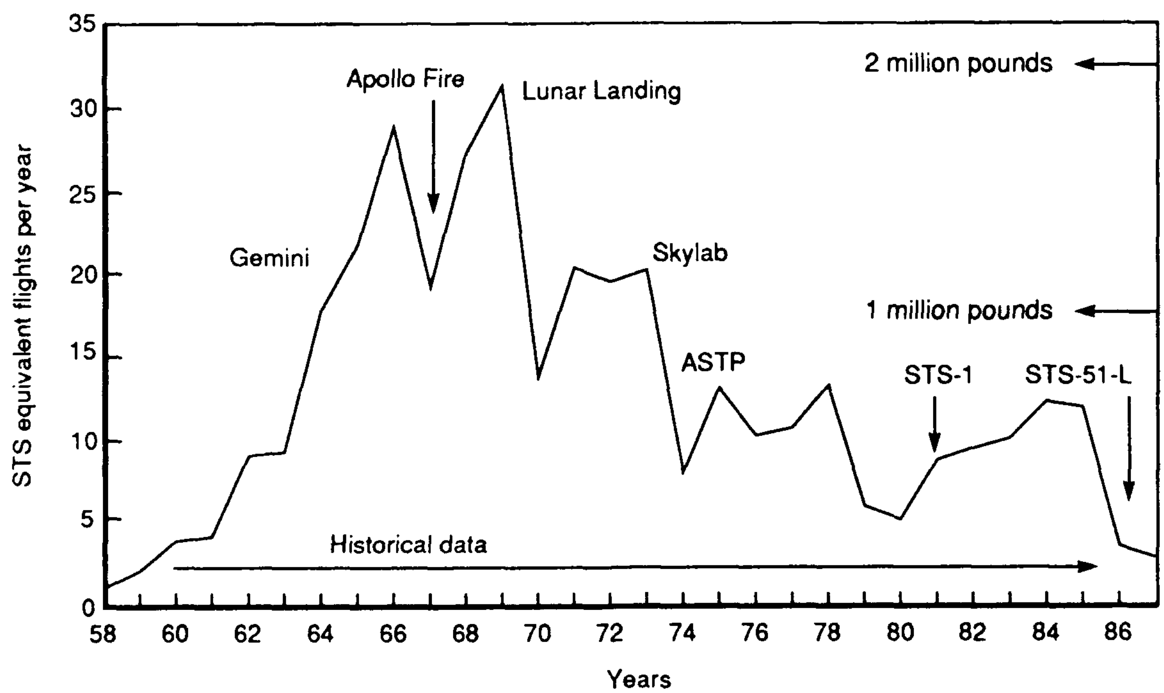


Fig. A.4—U.S. space efforts 1958–1987 (STS equivalent flights)

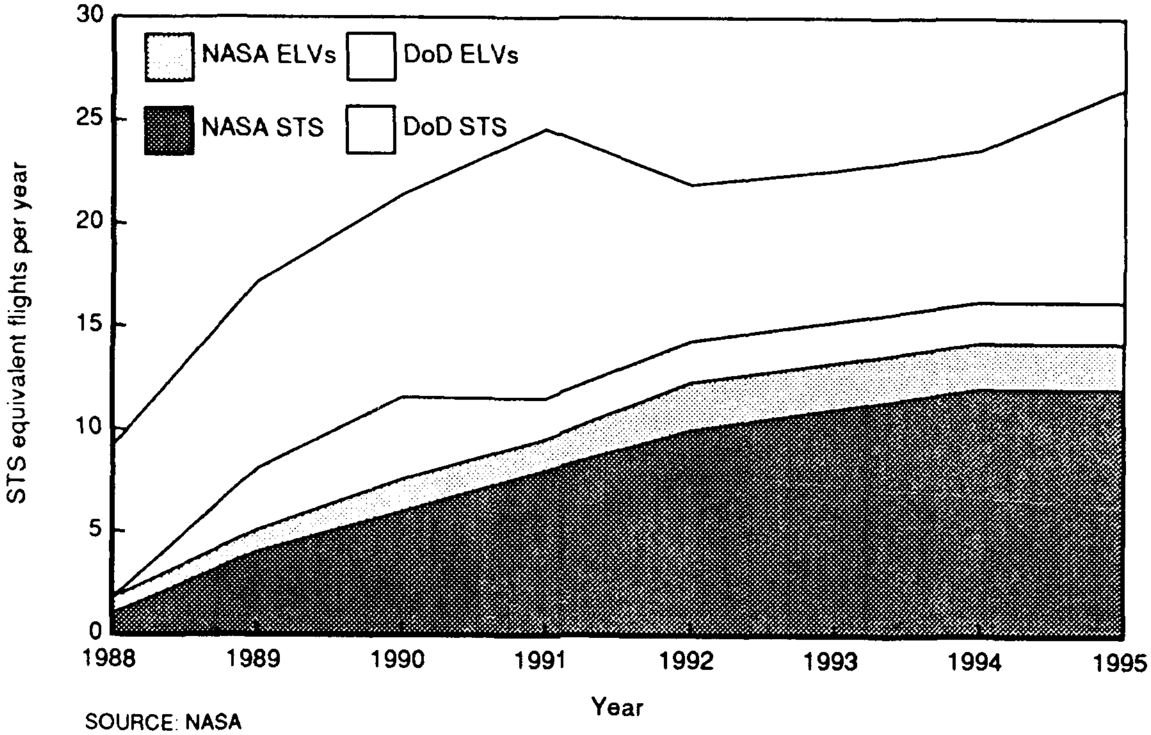
Table A.3

PROJECTIONS OF U.S. SPACEFLIGHTS, 1988–1995

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2																	
3											Comments						
4		STS Equiv	1988	1989	1990	1991	1992	1993	1994	1995							
5	NASA Shuttle	1	1	4	6	8	10	11	12	12		3.88 Manifest					
6	DoD Shuttle		0	3	4	2	2	2	2	2							
7	STS Equiv		1	7	10	10	12	13	14	14							
8	NASA ELVs																
9	Scout	0	2	2	2	2	2	2	2	2		3.88 Manifest to 90, Phase II for 91-95					
10	STS Equiv		0	0	0	0	0	0	0	0							
11	Delta	0.25	2	1	1	1	3	3	3	3		3.88 Manifest to 89, Phase I for 90-91, Phase II for 92-95					
12	STS Equiv		0.5	0.25	0.25	0.25	0.75	0.75	0.75	0.75							
13	Atlas Centaur	0.5	0	1	2	1	1	1	1	1		3.88 Manifest to 92, Phase II for 92-95					
14	STS Equiv		0	0.5	1	0.5	0.5	0.5	0.5	0.5							
15	Atlas E F	0.3	1	1	1	0	1	0	0	0		3.88 Manifest					
16	STS Equiv		0.3	0.3	0.3	0	0.3	0	0	0							
17	Titan 34D	0.75	0	0	0	1	1	0	0	0		3.88 Manifest, Phase I to 92					
18	STS Equiv		0	0	0	0.75	0.75	0	0	0							
19	Titan IV	1	0	0	0	0	0	1	1	1		3.88 Manifest, Phase II for 93-95					
20	STS Equiv		0	0	0	0	0	1	1	1							
21																	
22	STS Equiv 1		1.8	8.05	11.55	11.5	14.3	15.25	16.25	16.25							
23																	
24	DoD ELVs										1988-95	Total Vehicles		Source	Current Buy		
25	MLV I	0.25	0	4	4	5	4	4	4	4		23	MLV 1	AWST 2/1/88	29	3.5 yr. KSC	
26	STS Equiv		0	1	1	1.25	1	1	1	1							
27	MLV II	0.5	0	0	0	3	3	1	1	1		9	MLV 2	AWST 2/1/88	11	[illegible]	
28	STS Equiv		0	0	0	1.5	1.5	0.5	0.5	0.5							
29	Titan II	0.3	2	2	2	2	2	2	2	2		16	Titan II	AWST 2/1/88	14	2.5 yr. WTR	
30	STS Equiv		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6							
31	Titan IV	0.75	0	3	5	8	6	7	7	11		47	Titan IV	AWST 2/1/88	4	5.5 yr. WTR/KSC	
32	STS Equiv		0	2.25	3.75	6	4.5	5.25	5.25	8.25							
33	Titan 34D	0.75	9	7	6	5	0	0	0	0		27	Titan 34D	[illegible]			
34	STS Equiv		6.75	5.25	4.5	3.75	0	0	0	0							
35																	
36	STS Equiv 2		7.35	9.1	9.85	13.1	7.6	7.35	7.35	10.35							
37																	
38	Total Effort		9.15	17.15	21.4	24.6	21.9	22.6	23.6	26.6							
39	Total Launches		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	34	35	39							
40																	
41			1988	1989	1990	1991	1992	1993	1994	1995							
42	NASA STS		1	4	6	8	10	11	12	12							
43	NASA ELVs		0.8	1.05	1.55	1.5	2.3	2.25	2.25	2.25							
44	DoD STS		0	3	4	2	2	2	2	2							
45	DoD ELVs		7.35	9.1	9.85	13.1	7.6	7.35	7.35	10.35							
46	Total		9.15	17.15	21.4	24.6	21.9	22.6	23.6	26.6							
47																	
48					DoD Vehicles						Total 91-95	DoD Vehicles					
49					STS	2	2	2	2	2	10	STS					
50					MLV I	5	4	4	4	4	21	MLV I					
51					MLV II	3	3	1	1	1	9	MLV II					
52					Titan II	2	2	2	2	2	10	Titan II					
53					Titan IV	8	6	7	7	11	39	Titan IV					
54					Titan 34D	5	0	0	0	0	5	Titan 34D					
55																	
56					NASA Vehicles							NASA Vehicles					
57					STS	8	10	11	12	12	53	STS					
58					Delta	1	3	3	3	3	13	Delta					
59					Atlas Centaur	1	1	1	1	1	5	Atlas Centaur					
60					Atlas	0	1	0	0	0	1	Atlas					
61					Titan 34D	1	1	0	0	0	2	Titan 34D					
62					Titan IV	0	0	1	1	1	3	Titan IV					
63					Scout	2	2	2	2	2	10	Scout					
64																	
65																	
66																	
67																	
68																	
69																	
70																	
71																	

Table A.3—(continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
72		The Manifest as of Feb 1985															
73		STS Equiv	88	89	90	91	92	93	94	95							
74	STS	1	20	24	24	24	24	24	24	24							
75			20	24	24	24	24	24	24	24							
76	Titan 34D 7	0.75	1	1	2	2	3	2	2	2							
77			0.75	0.75	1.5	1.5	2.25	1.5	1.5	1.5							
78	Titan II	0.3	[illegible]	0	2	2	2	2	2	2							
79			0	0	0.6	0.6	0.6	0.6	0.6	0.6							
80	Atlas	0.3	1	2	1	0	0	0	0	0							
81			0.3	0.6	0.3	0	0	0	0	0							
82																	
83	No. Flights		22	27	29	28	29	28	28	28							
84	STS Equiv		21.05	25.35	26.4	26.1	26.85	26.1	26.1	26.1							
85			88	89	90	91	92	93	94	95							
86		STS	20	24	24	24	24	24	24	24							
87		Titan	0.75	0.75	1.5	1.5	2.25	1.5	1.5	1.5							
88		Titan II	0	0	0.6	0.6	0.6	0.6	0.6	0.6							
89		Atlas	0.3	0.6	0.3	0	0	0	0	0							
90																	
91																	
92		DoD Manifest March 1988		Official Unclassified from Air Staff													
93			1988	1989	1990	1991	1992	1993	1994	1995							
94	Equiv STS	DoD STS	0	3	4	3	2	2	2	2							
95	Equiv STS	DoD ELVs	7.05	8.55	10.8	9.55	8.85	7.4	7.25	10.15							
96	0.25	MLV 1	0	6	6	4	3	3	3	2							
97	0.5	MLV 2	0	0	0	3	[illegible]	1	1	1							
98	0.3	Titan 2	1	1	1	1	[illegible]	3	0	3							
99	0.75	Titan 4	0	2	[illegible]	7	[illegible]	6	[illegible]	10							
100	0.75	Titan 34D	9	[illegible]	5	2	2	1	1	[illegible]							
101																	
102			88	89	90	91	92	93	94	95							
103	NASA STS		1	4	6	7	10	11	12	12							
104	NASA ELVs		0.8	1.05	[illegible]	1.5	2.1	[illegible]	[illegible]	[illegible]							
105	DoD STS		0	3	4	3	2	2	2	2							
106	DoD ELVs		7.05	8.55	10.8	9.55	8.85	7.4	7.25	10.15							
107	Total		8.85	16.6	22.35	21.05	[illegible]	[illegible]	[illegible]	[illegible]							
108																	
109	U.S. Commercial ELVs																
110			[illegible]	[illegible]	[illegible]	1991											
111	Total	Commercial	[illegible]	4.25	[illegible]												
112		Delta (.25)	[illegible]	5	1												
113		A C (.5)	1	[illegible]	[illegible]												
114		Titan (.75)	1	2													



SOURCE: NASA

Fig. A.5—U.S. manifested flights, 1988–1995

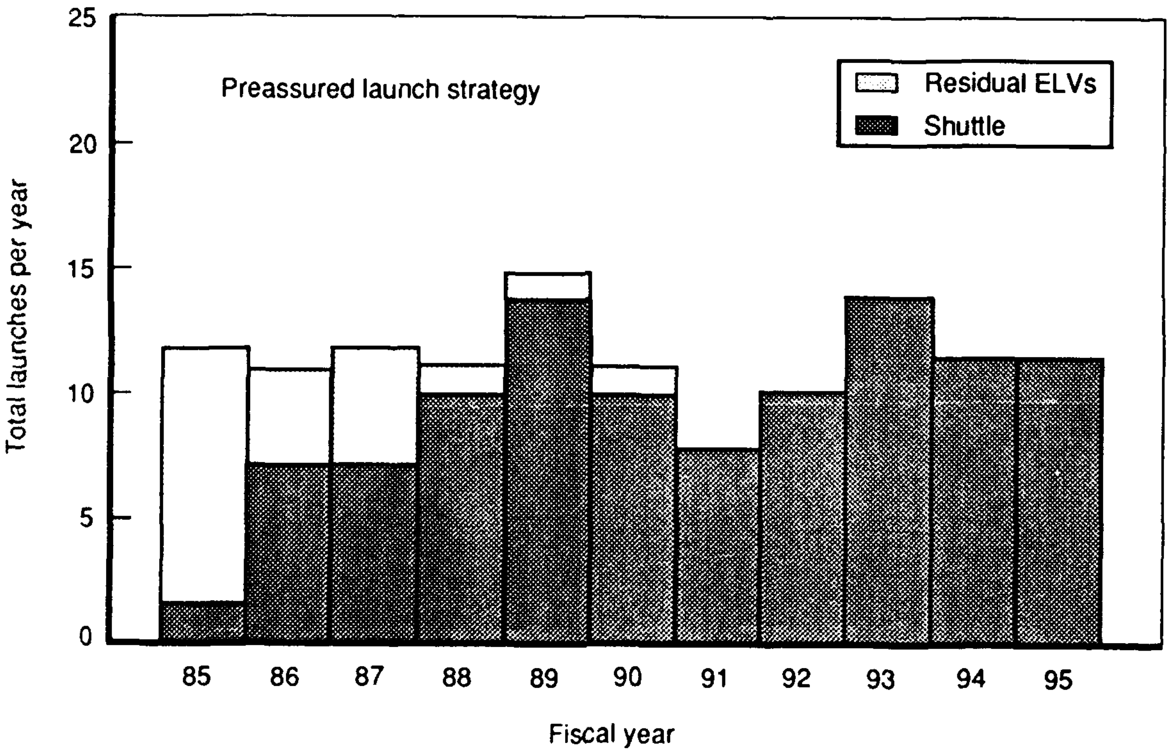


Fig. A.6—1983 DoD mission model preassured launch strategy

of DoD payloads in 1983 with residual ELVs being phased out and all payloads moving to the shuttle. Figure A.7 shows the result of DoD efforts to maintain a few ELVs (particularly refurbished Titan 2s and the new Titan 4) for some DoD payloads. Figure A.8 shows the results of the Challenger accident and ELV losses in 1986. The DoD added the MLV 1 and 2 vehicles to its launch fleet, resulting in the overall distribution shown in Fig. A.5. The DoD has argued that additional ELVs were needed to launch the backlog from the recent standdowns, as well as the lower shuttle flight rate and upweight performance expected in the aftermath of Challenger's loss.

Another interesting point is the increasing use of larger launch vehicles, implying a corresponding increase in the size of payloads. Through 1991, most launch effort is projected to go toward lowering the backlog from the 1986 accidents, and then stabilize around 24 STS equivalent flights per year. The latter number is also the figure NASA was aiming for when the shuttle was to carry all payloads and ELVs were phased out.

Figure A.9 compares the number of launches planned in the current manifest to historical data. The pace of launch activity is projected to rise to somewhat above that of the 1970s, but below that of the 1960s. Figure A.10 is from the same data as Fig. A.9, but converted into STS equivalent flights. While the *number* of launches per year are about that of the 1970s, *vehicle payloads* have grown significantly. In fact, in STS equivalents, the effort projected for the mid-1990s is comparable to the Apollo era. This reflects both the space station program as well as an increasing DoD use of space systems. Payloads have grown in size as well as sophistication as they meet more demanding mission requirements, whether civil or military.

The DoD and NASA intend to use different mixes of launch vehicles in the early 1990s. Launch vehicles for civil (including government-launched commercial payloads) and military users were totaled for the 1991–1995 period. The pie charts in Figs. A.11 and A.12 show the distribution of vehicle usage for NASA and the DoD, respectively. After the STS, NASA intends to fly many of its payloads on Deltas and Scouts (currently the smallest orbital launcher). Heavier ELVs are slated mostly for planetary science missions that use large upper stages such as the Centaur. The latter was removed from shuttle flights after the Challenger accident because of safety concerns with its cryogenic stage.[9]

In contrast to NASA, the DoD is spreading its payloads over a wider variety of vehicles. The smallest is the Titan 2, a converted ICBM, whereas the most common is the Titan 4. Several of these vehicles are the primary means of transport for some satellite programs. For example, the MLV 1 is used to launch Navstars for the Global Positioning System (GPS); MLV 2 will be employed to launch the DSCS communications satellite program, and Titan 2s are used for DMSP weather satellites.

A.5 DEMAND BEYOND 1995—THE STAS MODELS

Moving beyond 1995 involves considering a wide range of future space traffic scenarios. As discussed in Sec. II, the U.S. government recognized the need to assess a variety of options for building a space transportation "infrastructure." In May 1985, National Security Decision Directive (NSSD) 164 directed the DoD and NASA to conduct a joint study of space transportation architectures for the 1995–2010 time frame. Four contractors were selected, two of them (Rockwell and Boeing) managed through the U.S. Air Force Space Division and the other two (General Dynamics and McDonnell-Douglas) through NASA's Marshall Spaceflight Center.

As part of the Space Transportation Architecture Studies (STAS), standardized mission models of future space traffic levels were prepared. The STAS mission models consisted of

[9]Earlier versions of the Centaur are still used as upper stages on the Atlas ELV.

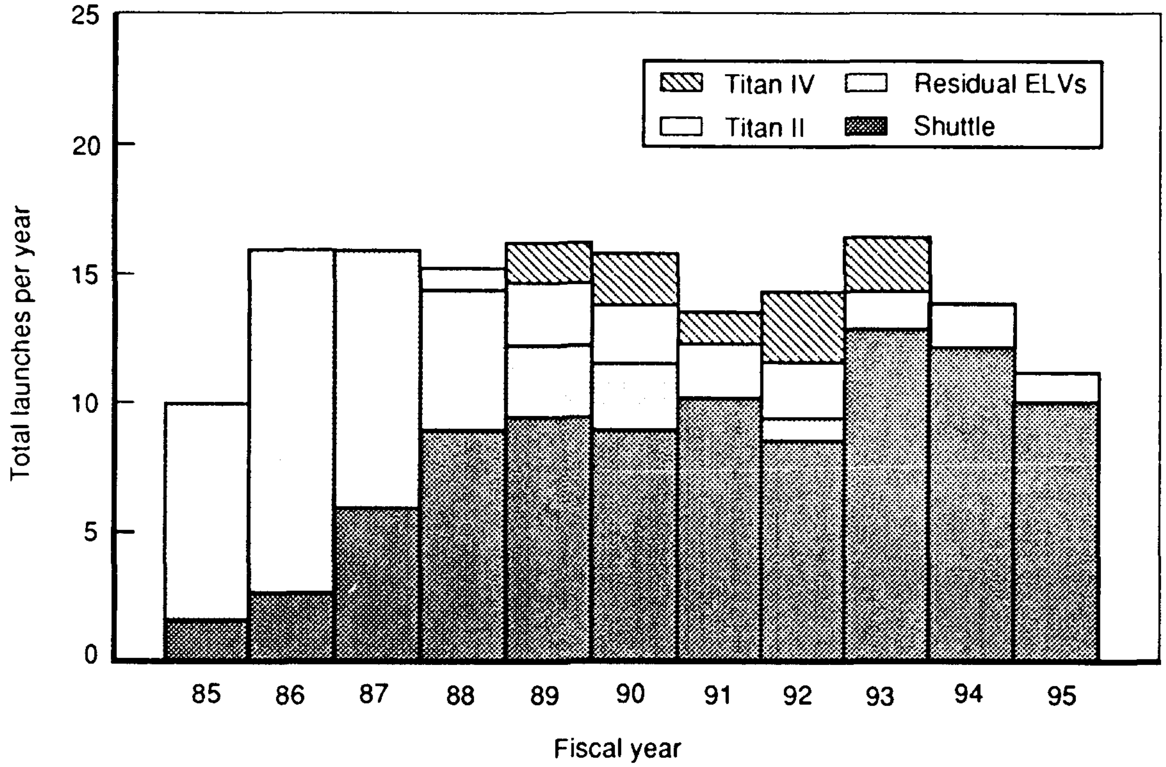


Fig. A.7—January 1986 DoD mission model

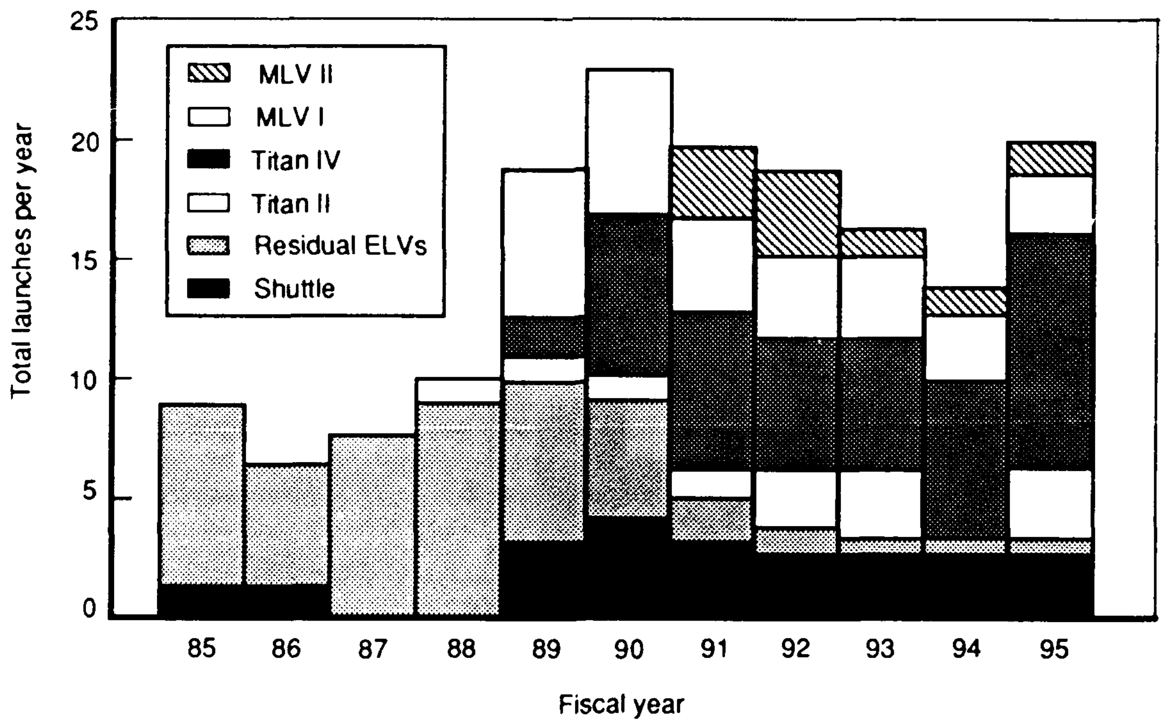


Fig. A.8—March 1988 DoD mission model

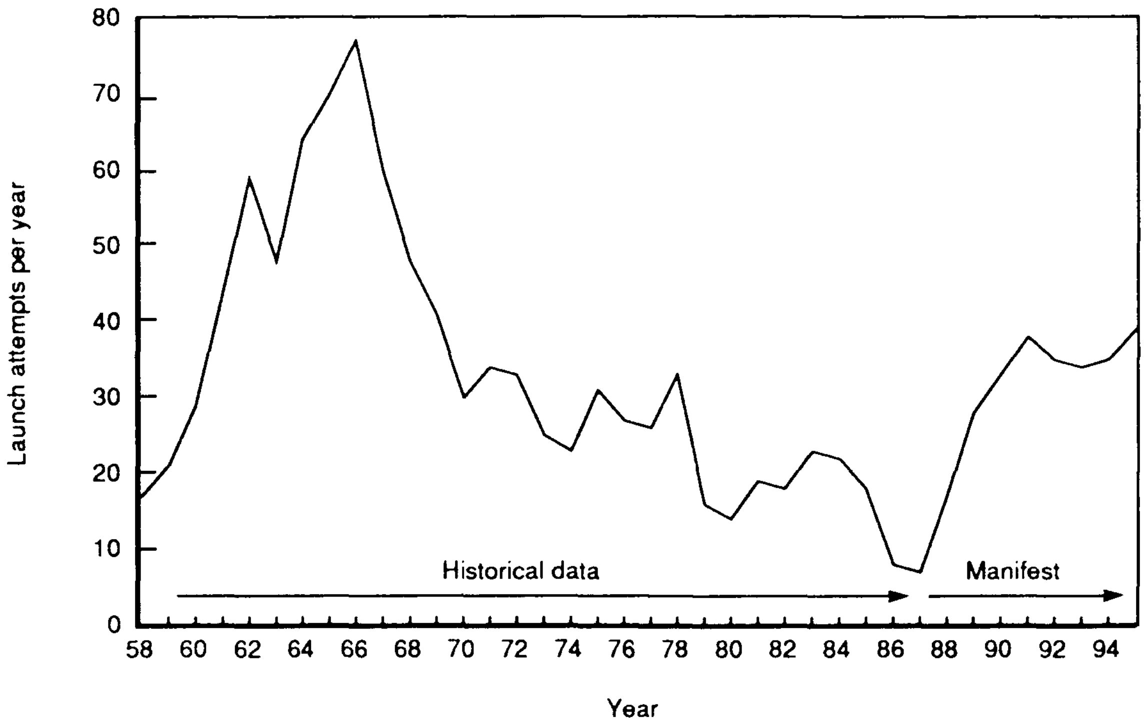


Fig. A.9—U.S. space launches, 1958–1995 (launch attempts)

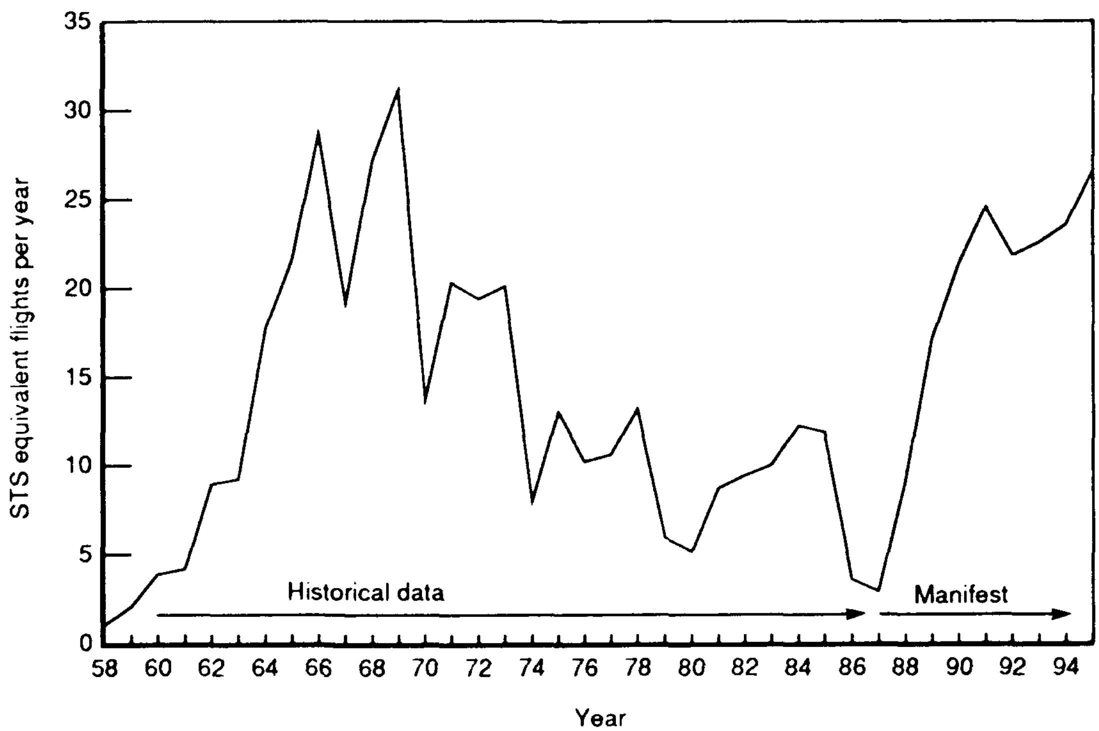


Fig. A.10—U.S. space launches, 1958–1995 (STS equivalent flights)

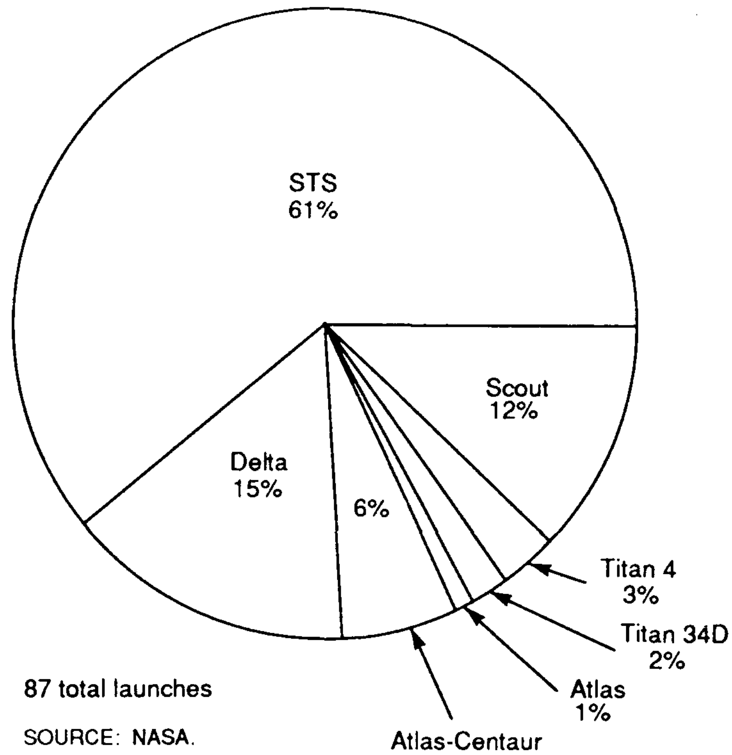


Fig. A.11—NASA launch vehicles, 1991–1995

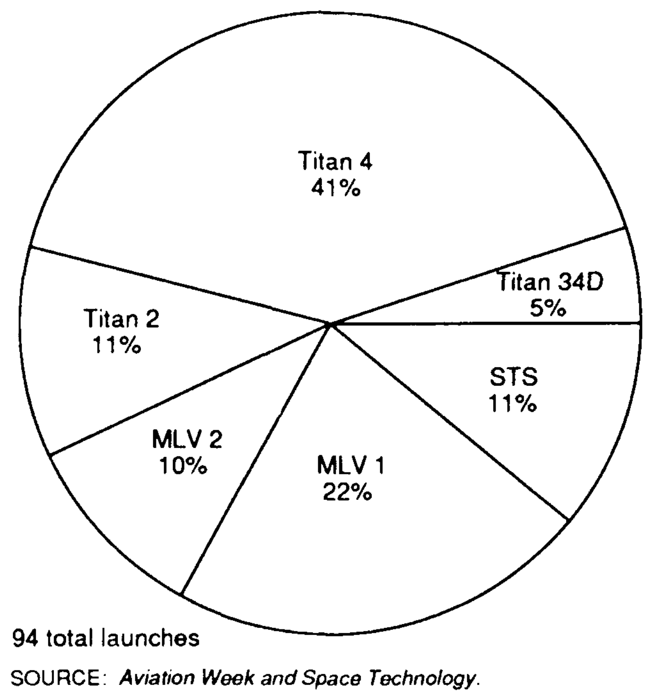


Fig. A.12—DoD launch vehicles, 1991–1995

two distinct civil and military data bases, each defining four major levels of activity: (1) constrained, (2) normal growth, (3) first-order expansion, and (4) second-order expansion. Figure A.13 is a summary matrix of the alternative combinations considered for detailed examination by the STAS contractors. The level III NASA effort included a lunar base, and level IV included a manned mission to Mars. The latter options were added as part of the Civil Space Leadership Initiative, an outgrowth of the "Ride Report."[10] An additional scenario of "normal DoD growth" combined with a "modest NASA expansion," a 2/III option according to Figure A.13, was added for this study.

Figure A.14 is an overview of the extreme ranges of the STAS models in STS equivalent flights. Pounds per year to orbit were divided by an assumed nominal shuttle capacity of 55,550 lb to LEO. Historical and manifest data points have been included for comparison.[11] Constrained demand assumed that no new initiatives were undertaken in payload development or in-space facilities and vehicles by either NASA or the DoD. The Phase 1 space station is included, however, with minimal support flights. The full SDI demand level not only assumed a major deployment of strategic defenses, but normal growth for the civil sector. Normal growth includes the Phase II space station, but no new manned initiatives.

Figure A.15 compares STAS mission models excluding SDI deployments with historical and manifest data. The gap between the last year of the 1988 manifest (1995) and the first year shown of the STAS models (1996) results from the gap in their preparation dates. No one has yet shown how the United States could or should transition from the manifest's forecast to longer range forecasts of space transportation. This lack of planning is a major concern of this study.

The main points to note in Figure A.15, however, are the different average levels of activity compared with that of the manifest. The constrained level is about a third below that of the manifest. The nominal demand shows a wide variation, but increasing to the manifest levels by 2010. The combination of a lunar base and nominal DoD demand in the early 21st century would be comparable to the early 1990s manifest.

One problem in these comparisons may be that the assumed shuttle capacity is too high. Although the shuttle (except for the heavier Columbia Orbiter) can carry 55,500 lb, in actual operations it runs about 75 percent full because of packing problems and payload incompatibilities. If the shuttle's capacity is reduced to a more realistic 41,500 lb to LEO, the number of STS equivalent flights for the STAS model would rise correspondingly. The constrained model would be only half of the manifest demand, rather than a third. The nominal civil/military model would roughly match that of the manifest, and the lunar base/nominal DoD option would represent significant new growth. Nevertheless, the relative positions of the STAS model levels among themselves would remain unchanged.

Figures A.16 through A.21 are plots of the STAS models, segmented by DoD and civil sectors. Only upweight requirements have been included, and not the small, albeit important, downweight requirements.[12] ELVs cannot bring back payloads as the shuttle can, so downweight missions are generally assumed to be shuttle missions. This may change in the future—commercial companies are examining the possibility of offering payload retrieval services using ballistic capsules.[13] Foreign nations may also vie for payload return missions with the European Hermes vehicle.

[10]Sally K. Ride, *Leadership and America's Future in Space*, NASA Headquarters, Washington, D.C., August 1987.

[11]Joint Task Team of NASA and the DoD, *National Space Transportation and Support Study, 1995–2010*, May 1986; and NASA Headquarters, *National Space Transportation and Support Study, Civil Needs Data Base, Version 2.1*, Vol. I, *Executive Summary*, Washington, D.C., July 16, 1987.

[12]Upweight consists of payload mass launched from Earth. Downweight consists of payload mass brought to Earth from space.

[13]"Euro capsules may offer low cost orbit time," *Space Business News*, April 17, 1989, pp. 3–4.

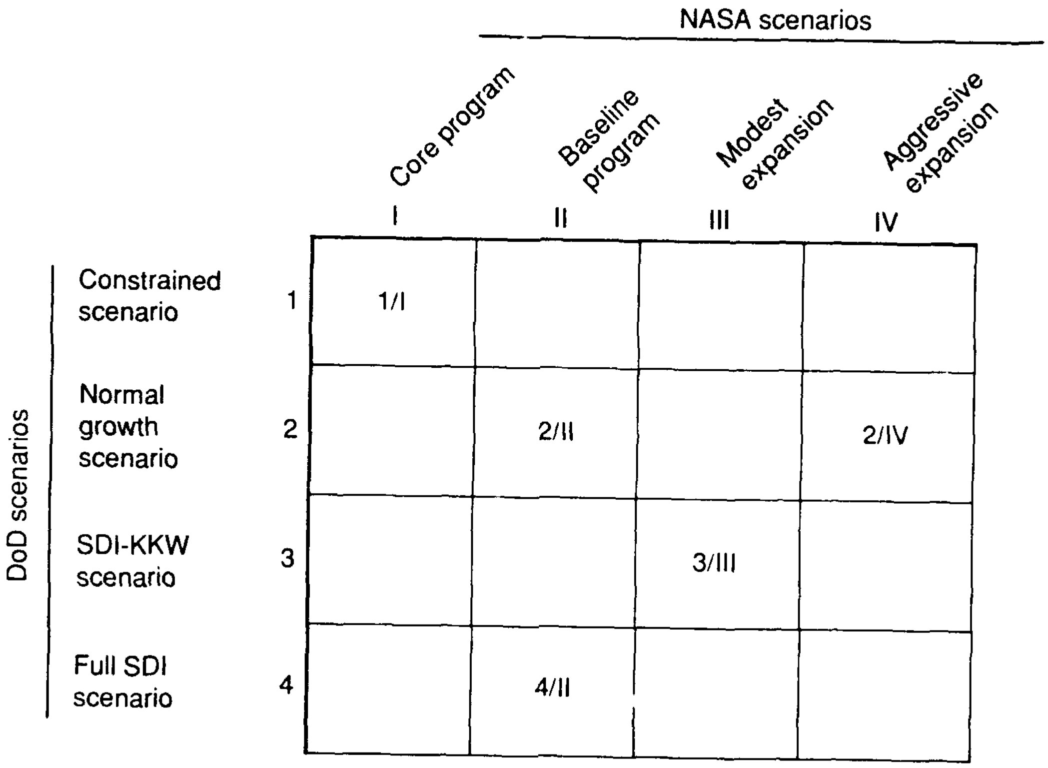


Fig. A.13—STAS matrix of NASA and DoD scenarios

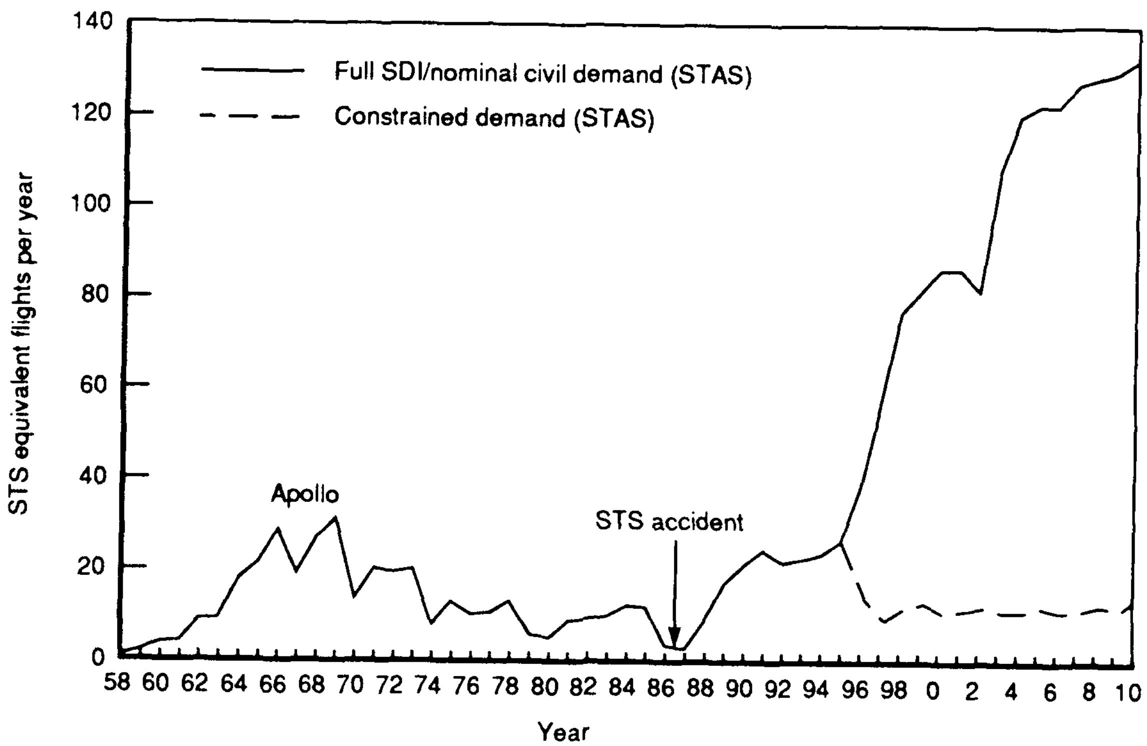


Fig. A.14—U.S. launch demand ranges

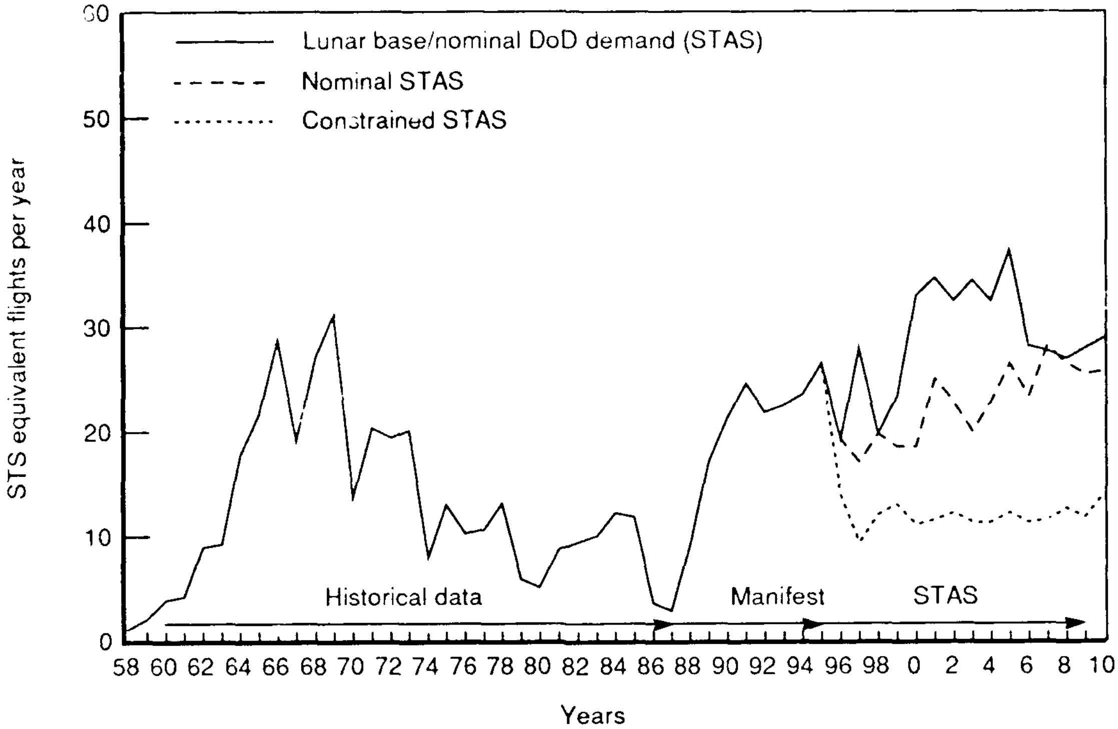


Fig. A.15—U.S. launch demand and non-SDI STAS models

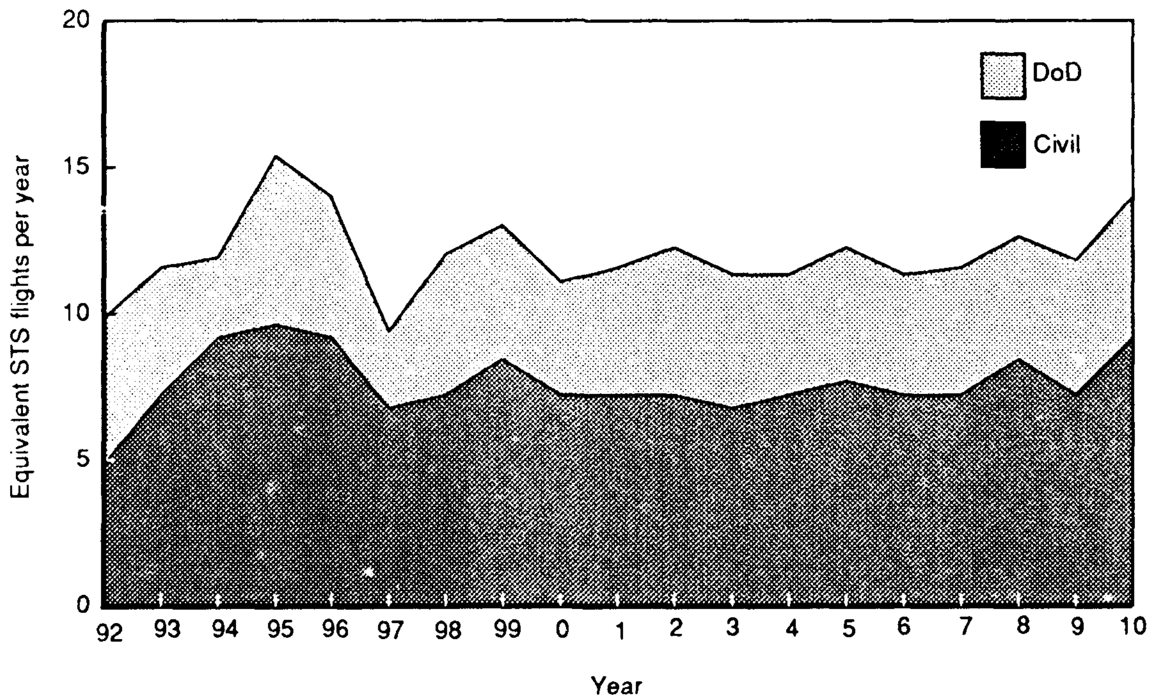


Fig. A.16—Constrained demand (STAS)

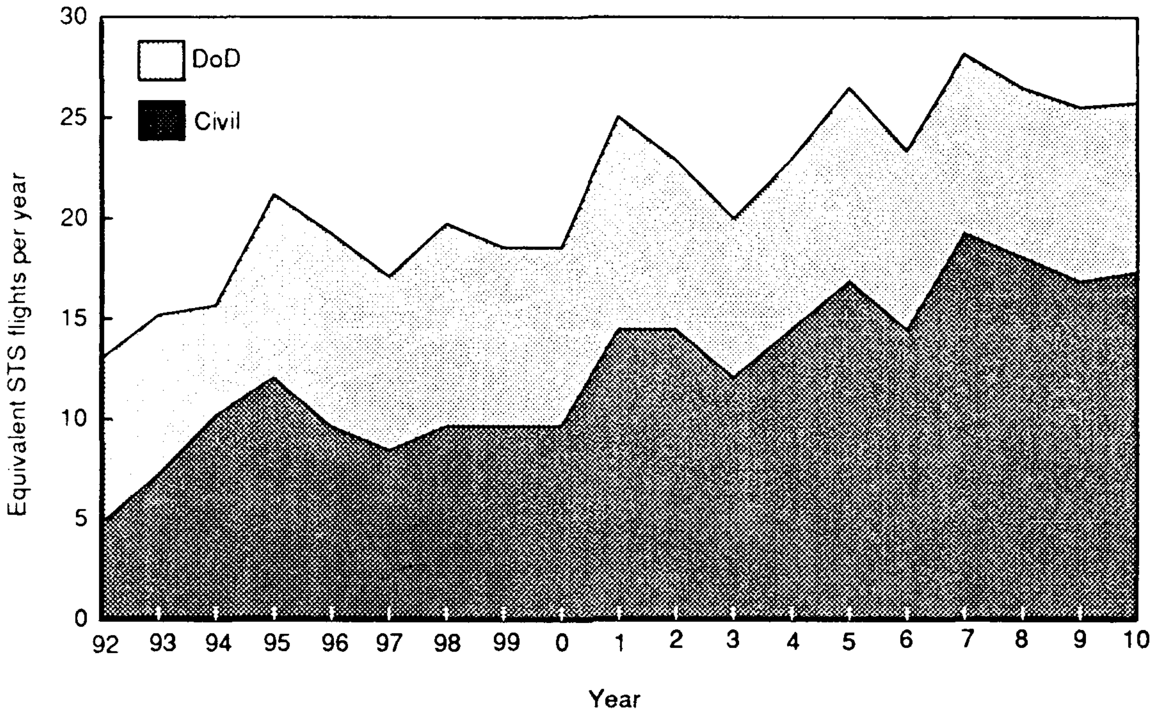


Fig. A.17—Nominal demand (STAS)

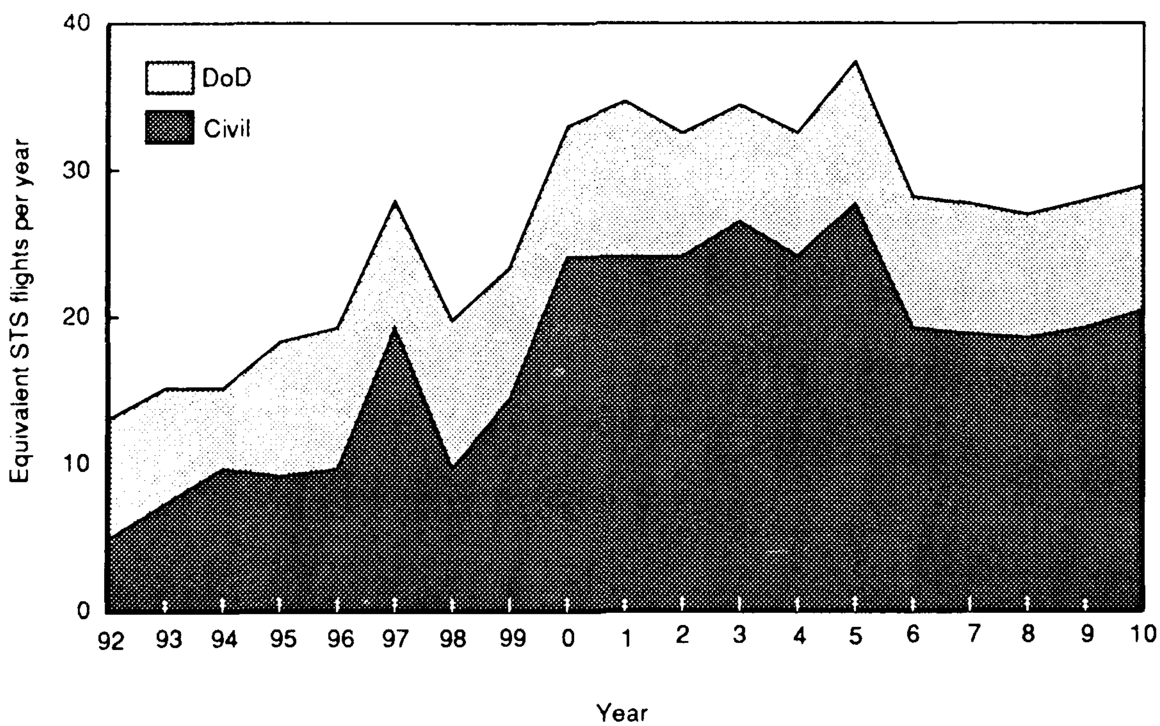


Fig. A.18—Lunar base/nominal DoD demand (STAS)

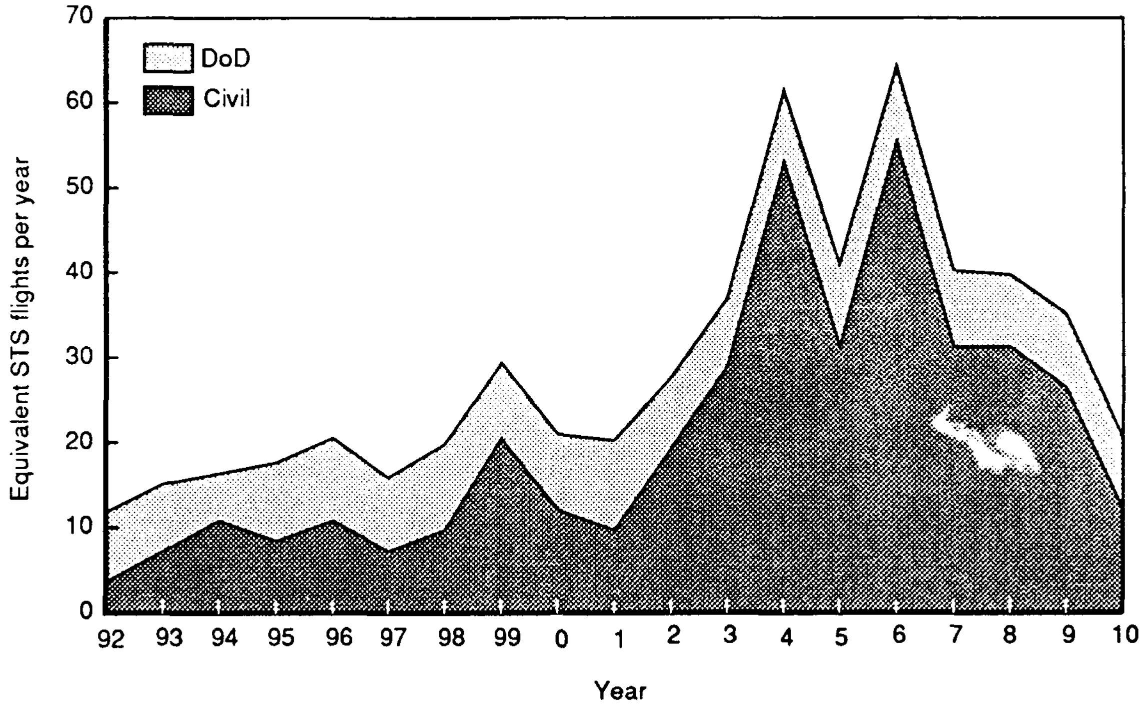


Fig. A.19—Mars mission/nominal DoD demand (STAS)

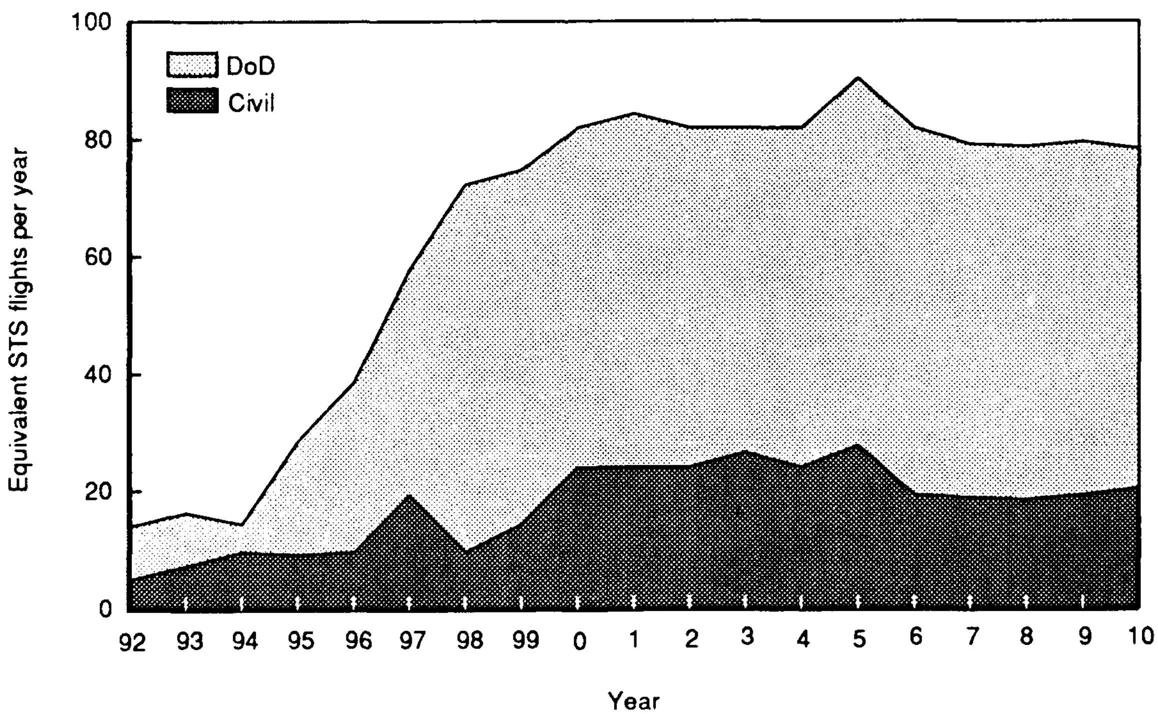


Fig. A.20—Lunar base/SDI-KKV demand (STAS)

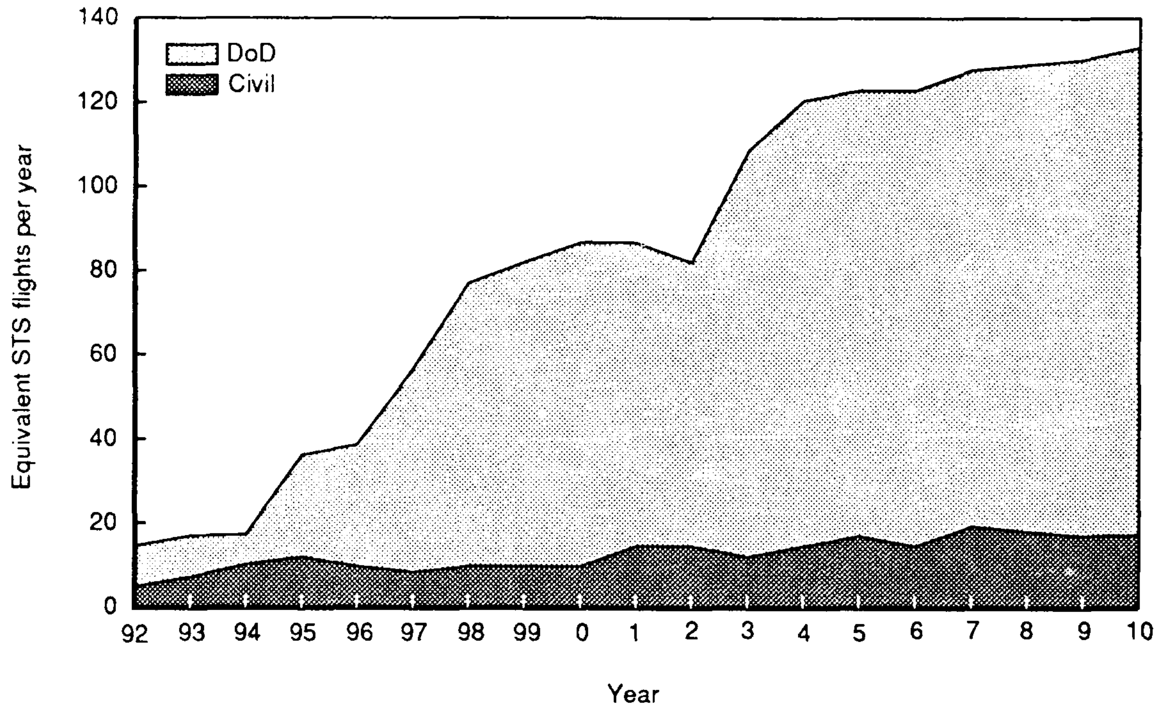


Fig. A.21—Full SDI/nominal civil demand (STAS)

A.6 THE ADVANCED LAUNCH SYSTEM MISSION MODEL

One result of the STAS studies was a recommendation to build a heavy-lift launch vehicle that could also lower the cost of placing payloads in orbit. As the Air Force began an effort to develop such an Advanced Launch System, a simple mission model was prepared. The model was left intentionally vague to allow contractors maximum flexibility in achieving cost-savings and payload accommodation.[14] Additionally, there was some belief that payloads would accommodate themselves to the launcher, provided manufacturers and users had some assurances the vehicle would actually be available.

Figure A.22 is a plot of the ALS mission model taken from an ALS requirements document; its expanded levels are dramatically above peak historical levels of 1–2 million pounds per year.[15] Even the "normal" level could cover the efforts of *all* currently planned vehicles. Figure A.23 is the same data converted into STS equivalent flights, subject to a caveat on the assumed shuttle payload capacity which may be an understatement of the actual number of equivalent flights required. The ALS expanded level is similar to flight levels required by the full SDI option in the STAS mission model. Figure A.24 shows how both the normal and expanded ALS projections compare with both historical data and the 1988 manifest.

[14]U.S. Air Force Space Division, *Advanced Launch System Requirements Document (Preliminary)*, SD-ALS-R-SRD-v1.00, El Segundo, CA, March 3, 1988.

[15]Ibid.

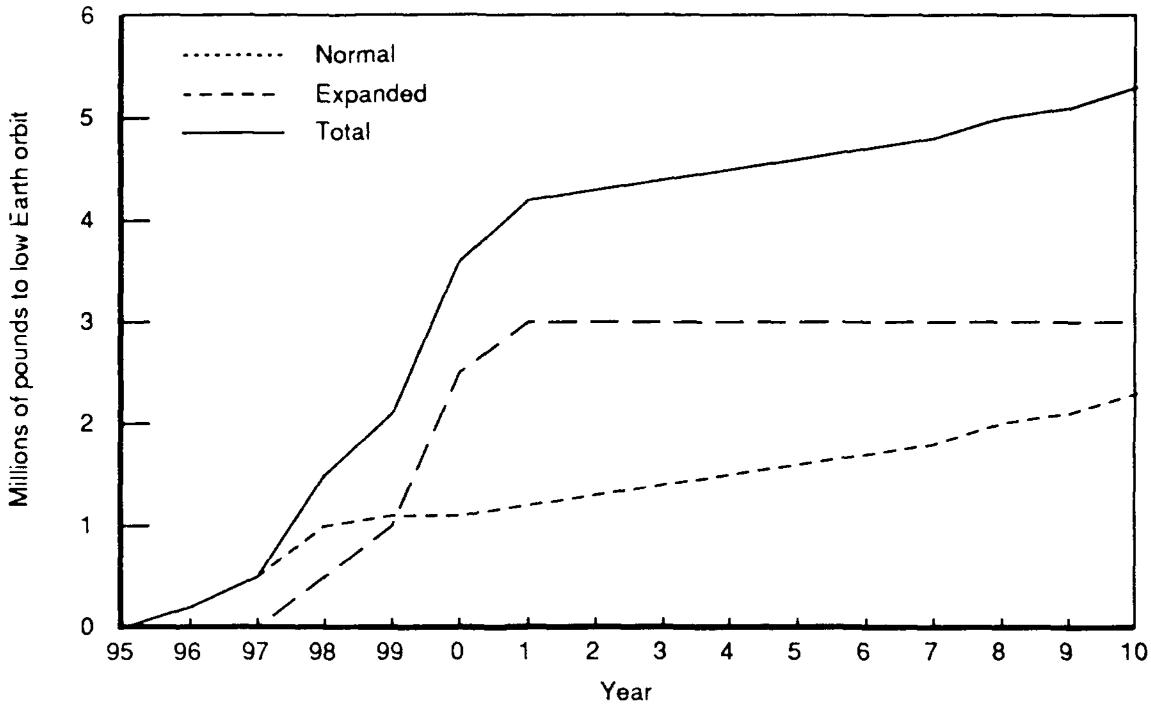


Fig. A.22—ALS phase II mission model (millions of pounds)

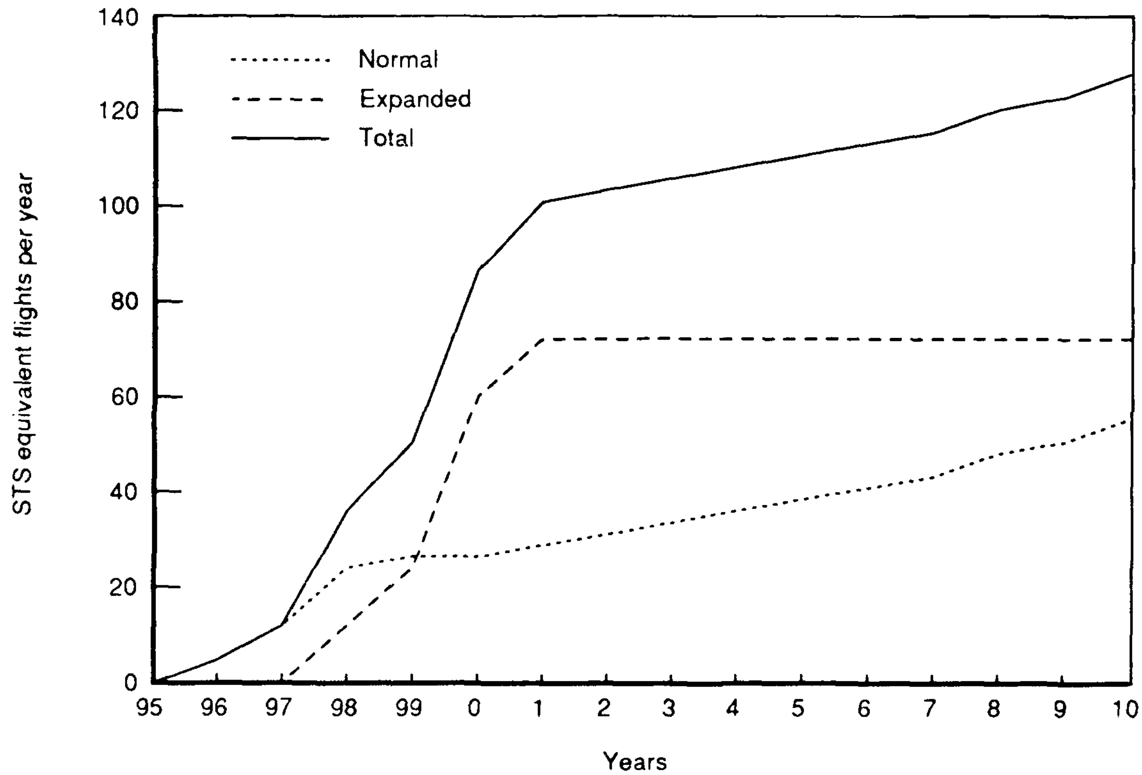


Fig. A.23—ALS phase II mission model (STS equivalent flights)

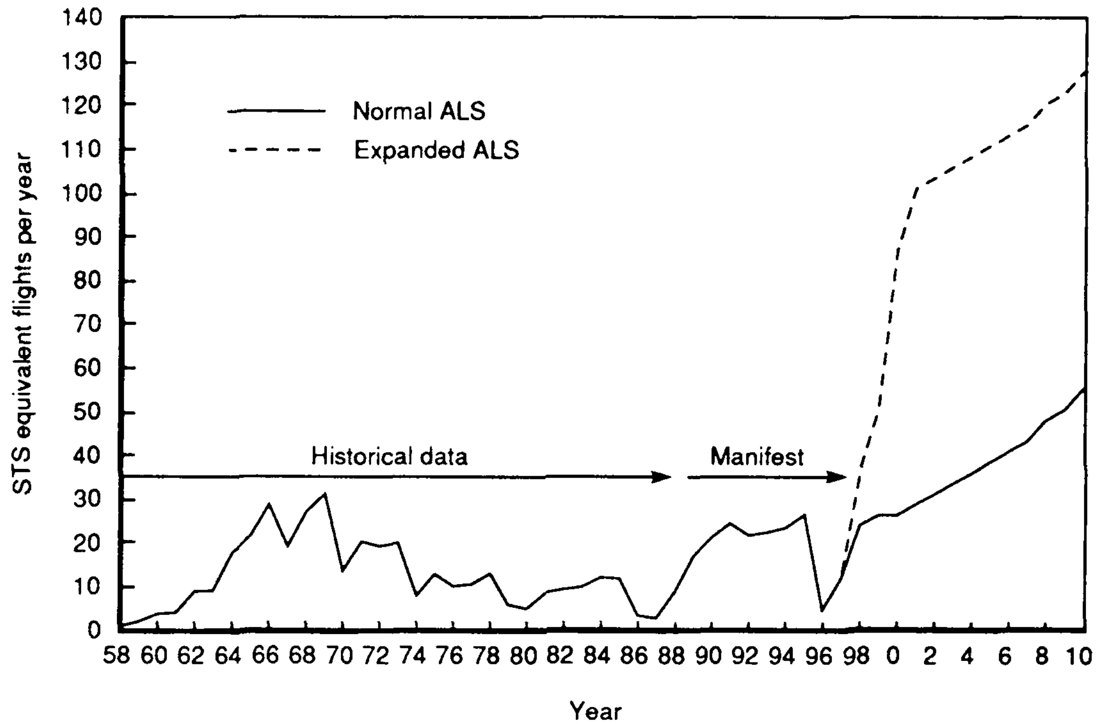


Fig. A.24—U.S. launch demand and ALS models

A.7 SUMMARY

Figure A.25 is a summary comparison of the non-SDI mission models from both STAS and ALS sources. Several observations can be drawn from comparing them with historical and manifested traffic levels:

- With the resumption of shuttle flights and the new ELVs, the level of space traffic (in STS equivalents) for the early 1990s will be comparable to the Apollo years, although the actual number of flights per year will be less.
- Transition plans to go from the current manifest to longer term plans have not been made. This creates a major discontinuity in the mid to late 1990s because of a lack of agreement on what goals the United States should be pursuing in space.
- The constrained STAS demand level would represent a major contraction in U.S. efforts, likely leaving a major overcapacity in launch capability.
- Nominal STAS demand and the lunar base/nominal DoD efforts are roughly comparable to currently planned levels of effort, with modest growth rates.
- In contrast to the nominal STAS models, the normal ALS model assumes steady and steep growth through 2010. This is less a representation of demand per se than a projection of traffic to be carried by the ALS. Just what that traffic would consist of, barring an SDI deployment, is unclear.

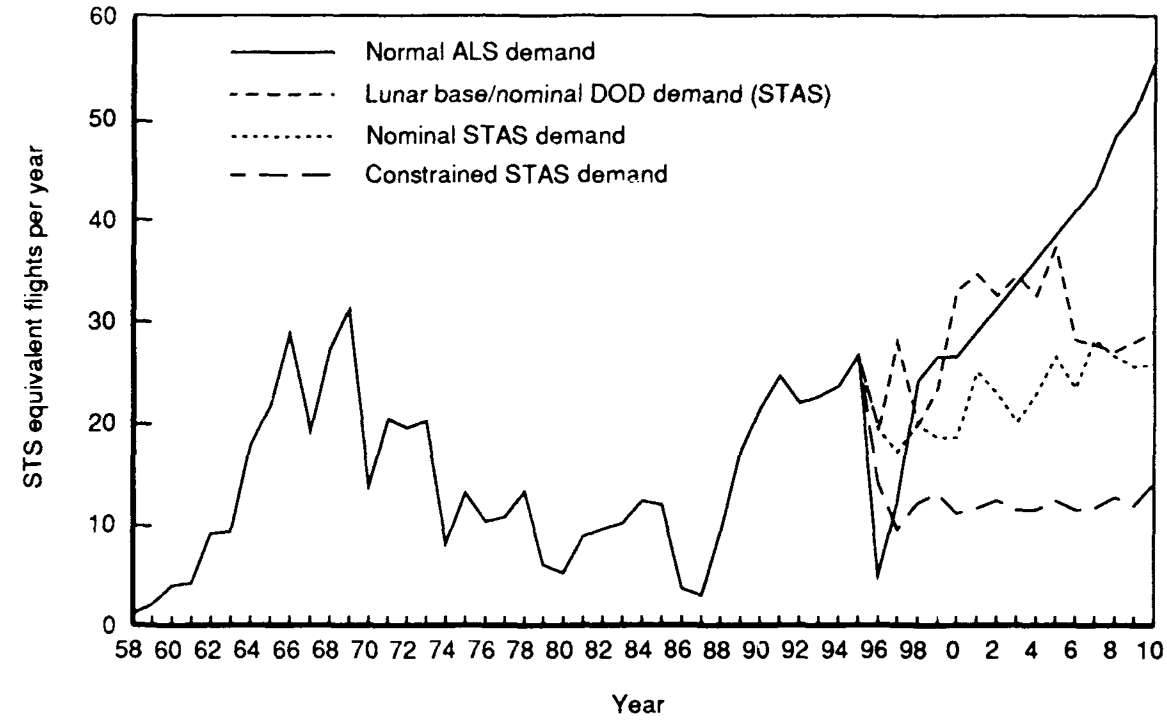


Fig. A.25—U.S. launch demand and nominal models

Figure A.26 compares mission models of greatly expanded civil and military space operations from both STAS and ALS sources. All the expanded effort models represent dramatic increases in space traffic over historical or currently planned levels. Various SDI deployments have the most influence on the models. The expanded ALS and full SDI models assume similar levels of effort through 2010. The STAS model assumes a more gradual buildup of traffic, while the expanded ALS model starts off immediately at a high level.

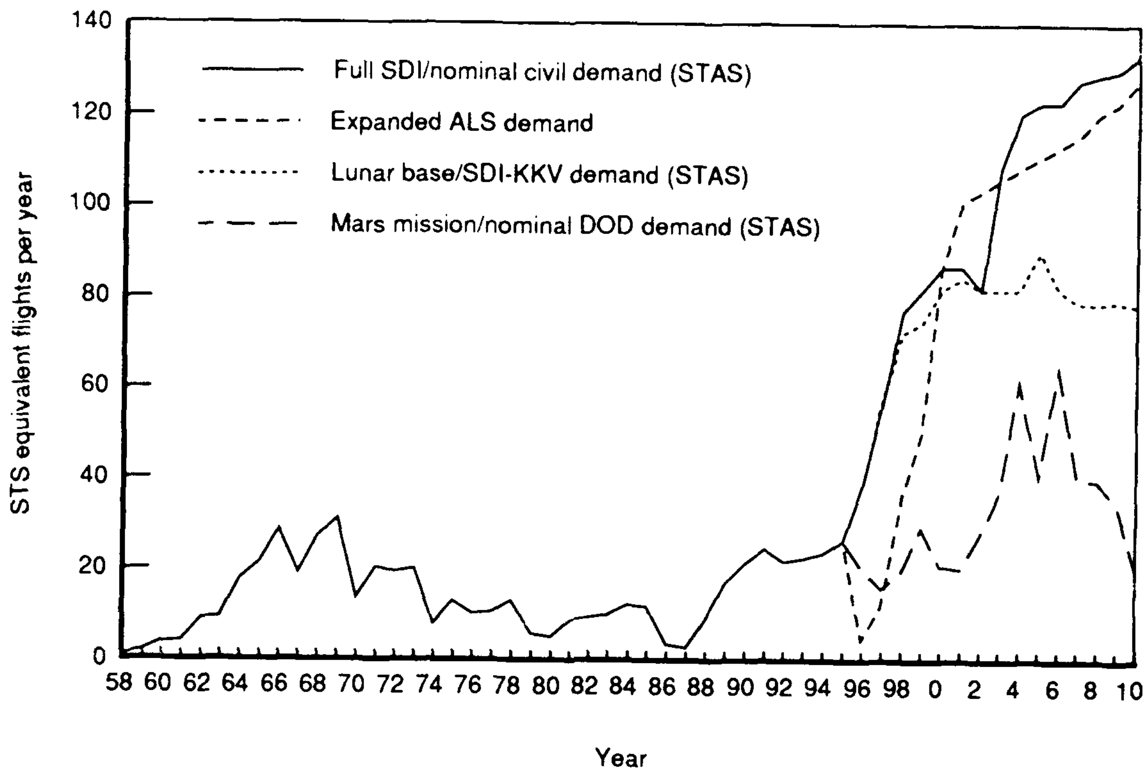


Fig. A.26—U.S. launch demand and expanded STAS/ALS models

Appendix B
COSTS TO LOW EARTH ORBIT

B.1 INTRODUCTION

Given the prospect of tight budgets for space activities, costs to orbit are of intense interest to transportation planners. Although transportation costs are only one portion of the total life-cycle costs for space systems, they are often cited as driving requirements such as system reliability, serviceability, and survivability. Many factors determine the overall effectiveness of space systems, yet cost alone is a major "first-order" filter on what launch vehicle options are feasible.

The purpose of this appendix is to provide estimates for the cost of reaching low Earth orbit (LEO) with various existing and planned launch vehicles. The vehicles are those likely to be available in the 1990–2010 period, although some vehicles may not cover the entire period. Cost estimates are made as a function of the total amount of payload mass launched to LEO. All costs are in constant 1988 dollars. No attempt has been made to adjust for the time periods when these vehicles would be available or how rapidly they could deploy their payloads.

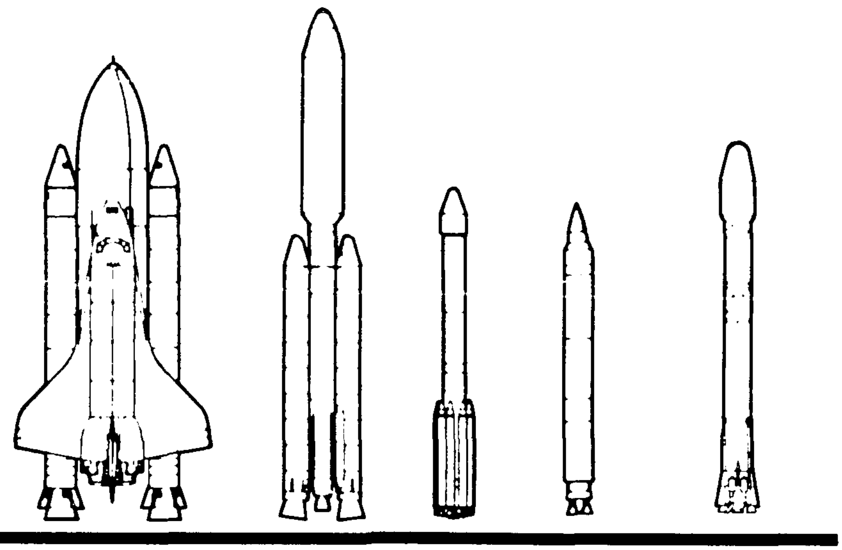
The cost estimates shown here are made from a broader perspective than those used to evaluate the cost of alternative launch vehicle mixes (see Sec. 4.4). In the case of existing launch vehicles, rate effects and production learning curves are included. These factors, which produce lower average costs at higher flight rates, were neglected in favor of constant recurring costs per flight in the main text. This results in cost estimates for existing vehicles being slightly higher, and thus more conservative, than those shown in this appendix.

The cost estimates for proposed vehicles include the amortization of nonrecurring costs as payloads are launched as well as learning curve effects. Launch rates are set by the demand levels (see Sec. 3.3) and are not allowed to grow unbounded. Partially in consequence, learning curve effects are dominated by the amortization of nonrecurring and fixed costs and were neglected for simplicity in the main text. Estimates of average recurring costs per flight for proposed vehicles are shown compared with projections of declining average costs as payloads are launched. Although constant recurring costs per flight are useful in comparing proposed vehicles to existing ones, it must be kept in mind that new vehicles must also account for associated nonrecurring costs. The launch vehicle cost figures used in the main text include estimates of the nonrecurring and recurring costs with each alternative vehicle mix.

By comparing cost projections across different traffic levels, a ranking of possible cost-effective vehicle mixes can be made. A major caveat, however, is that low cost is not the only criteria for choosing a vehicle. Other issues, such as overall system resiliency, performance, and policy objectives, need to be taken into account. The conclusions of this appendix were, however, consistent with the results of the evaluation process (see Sec. 6.2).

B.2 VEHICLES COMPARED

Of central interest were current launch vehicles such as the Titan 4, MLV 1 (also known as the Delta 2), and the STS, as shown in Fig. B.1. They are carrying the bulk of U.S. space traffic in the recovery period following the loss of the Challenger. Next were proposed vehicles such as the Shuttle-C (an unmanned cargo vehicle) and the Advanced Launch System. Their costs were compared to historical costs for the Saturn V and the STS program



	Space Shuttle	Titan 2	Delta 2	Titan 2	Atlas-Centaur 2
Payload to 100 n mi:					
KSC	(47-58K lb)	39,100 lb	11,400 lb	5,200 lb	14,900 lb
VAFB	NA	31,500 lb	--	4,200 lb	--
Available date:					
	1988 (1992 for 4th orbiter)	1989	1988	1988	1991

Fig. B.1—Recovery launch vehicles

(exclusive of upper stages, Spacelab, and associated elements). At this time, cost estimates were not available for the MLV 2, an Atlas 2 class vehicle, to derive estimates of comparable detail.[1] The Titan 2 was not included because it constitutes a one-time salvage of retiring ICBM launchers.

B.3 ASSUMPTIONS

The cost estimates in this appendix were based on the best available data, but they should be treated as only representative. Proposed programs like the ALS and Shuttle-C are still in development and their cost estimates are thus uncertain. Data sources included government reports, contractor reports, and interviews with government and industry personnel. In some cases, independent estimates have been made to fill in gaps from these sources.

Comparisons of launch vehicle costs are typically difficult to make because of uncertainties in defining what kind of cost is sought and normalizing the many differences between vehicles. Here all costs have been based upon placing a pound of payload in LEO at 100 n mi, after being launched due east out of Kennedy Space Center, Florida (i.e., at a 28.5 deg inclination). This reference orbit allows a direct comparison of launch vehicles with differing capacities.

Dollars per pound of payload are taken as a function of the cumulative amount of mass placed in orbit by the same vehicle design. Using cumulative mass avoids some of the

[1] "MLV 2 could generate another rocket class," *Space Business News*, September 28, 1987, pp. 1–3.

problems of defining a specific launch schedule that is scenario dependent. Various generic flight rates were assumed in generating the cumulative mass deployed to orbit with specific vehicles. These rates were those considered "nominal" for the vehicles and which did not involve additional nonrecurring costs for items such as new launch facilities and additional production tooling. Vehicles were assumed to fly full. Actual costs per pound would be slightly higher depending on manifesting efficiencies.

No assumptions were made about payload costs or vehicle reliabilities.[2] Allowance was made for the future inclusion of insurance costs to account for differences in reliability and system resiliency. Clearly, a vehicle may have a low cost per pound to orbit and yet be unacceptable because of an inadequate payload envelope (e.g., weight and volume constraints) or low reliability for the desired mission (e.g., manned flights). Risks due to vehicle losses and delays were not aggregated into vehicle costs in order that they could be treated separately in the evaluation of alternative vehicle mixes (see Sec. VI).

Given the wide variance in the periods for which the compared vehicles are available, costs were undiscounted in computing dollars per pound to orbit. Net present values for new programs were calculated using a 5 percent real discount rate, as is the practice of the Office of Management and Budget.[3] All dollars were converted to 1988 dollars via GNP deflators from the USAF Comptroller's Office.[4]

B.4 TITAN 4 LAUNCH VEHICLE

The Titan 4 launch vehicle is the latest in the long series of this family. In 1983, the Air Force was granted permission to develop a Complementary Expendable Vehicle (CELV) to provide an alternative to the shuttle for some payloads. The Martin-Marietta Titan 34D7 design was selected and later designated the Titan 4. The Air Force has ordered 23 vehicles and launched the first one in mid-1989.[5]

The Titan 4 consists of liquid propellent core stages with two solid rocket motor boosters that operate in parallel at liftoff. Current payload performance capabilities are 39,100 lb out of Kennedy Space Center (KSC) in a due east orbit to 100 n mi.[6] The Titan 4 can use a Boeing Inertial Upper Stage (IUS) or a General Dynamics Centaur G-prime upper stage. The latter can place up to 10,000 lb in a geosynchronous orbit. In using standard comparisons of LEO payload performance, however, this option was not relevant. Plans also exist to upgrade the solid rocket motors and to boost payload performance by 25 to 33 percent. This option was not covered as its costs and benefits are still unclear.[7]

Since the Titan family of vehicles has a long history, much of the DDT&E that would have been required to produce the Titan 4 from scratch has already been done. Those costs are "sunk" and the payload launch cost per pound of a Titan 4 is mostly due to current production, operations, and support expenses. Estimates of vehicle cost were derived from several government sources for flight rates of two to eight per year.[8] Current plans are for a flight rate of about five per year. Flights did not exceed 12 per year because that would have required additional nonrecurring costs to construct additional production facilities. At 12 per

[2]These issues are discussed in App. D.

[3]Quirk, James P., and Katsuaki L.Terasawa, *The Choice of Discount Rate Applicable to Government Resource Use*, The RAND Corporation, R-3464-PA&E, Santa Monica, CA, December 1987.

[4]U.S. Air Force, *The United States Air Force Summary, Fiscal Years 1988/89*, Deputy Comptroller of the Air Force for Cost and Economics, Economics and Field Support Division, Washington, D.C., 1987, p. A-11.

[5] "Martin Marietta Delivers First Titan 4 to Cape Canaveral Launch Site," *Aviation Week & Space Technology*, January 18, 1988, p. 19.

[6] Major General Robert Rankine, USAF, "Progress in Space," briefing to the National Space Club, Washington, D.C., June 22-24, 1987.

[7]Tim Furniss, "Replacing the Shuttle," *Flight International*, October 29, 1988, pp. 26–28.

[8]Interviews with E. Blond, Aerospace Corporation, and D. Gore, Rockwell International, on data for the NASA-DoD Space Transportation Architecture Study, October 1987.

year, facilities at KSC will be saturated and additional costs may be required for more pads. Finally, a 95 percent Crawford learning curve was assumed as launches occurred.[9]

A summary spreadsheet is attached as Table B.1. The cumulative amount of mass that could be launched was divided by cumulative costs incurred to obtain an average of cost per pound as a function of payload mass. At a cumulative level of about 7 million pounds, the cost per pound could get as low as $1800 per pound. As shown in Fig. B.2, this is less than half of the current cost per flight, $4200 per pound.

B.5 MEDIUM LAUNCH VEHICLE 1

In the wake of the Challenger loss, the Air Force held a competition to procure a new launch vehicle, primarily to continue the launch of Navstar satellites for the Global Positioning System (GPS). McDonnell-Douglas won the initial contract for seven Medium Launch Vehicles (MLVs) to be derived from the Delta 2. In February 1988, the Air Force exercised an option to buy an additional seven MLVs. A final option remains to buy six more vehicles.[10] Payload performance to 100 n mi altitude out of KSC is 11,400 lb.[11]

Like the Titan, the Delta ELV comes from a long family of earlier vehicles. Much of its DDT&E costs are sunk and the cost per pound is mostly due to production, operations, and support expenses. Estimates of vehicle cost were derived from several government sources for flight rates of two to eight per year.[12] Current plans are for a flight rate of about 12 per year given the two available pads at KSC (there is one more at Vandenberg AFB).[13] Production facilities, however, appear adequate for 18 vehicles per year. A 95 percent Crawford learning curve was again assumed.

A summary spreadsheet is attached as Table B.2. Again, the cumulative amount of mass that could be orbited was divided by cumulative costs incurred to get an average of cost per pound as a function of payload mass. At a cumulative level of about 2.5 million pounds, the payload launch cost per pound could go as low as $1800 per pound. As shown in Fig. B.2, this is slightly more than one-half the current $3100 per pound cost per flight.

B.6 SPACE SHUTTLE

The Space Transportation System (STS), or space shuttle, returned to flight in September 1988. All future shuttle flights will be launched from KSC as plans to use VAFB have been suspended. The Air Force Space Division and Congressional Budget Office estimate the shuttle cost per flight as approximately $245 million.[14] This figure assumes the DDT&E and recovery costs for the STS 51-L accident are sunk. No provisions are made for depreciation or capital charges to the STS.

Shuttle performance is assumed on the basis of deploying to a standard orbit with 104 percent rated space shuttle main engines (SSMEs) and standard solid rocket motors (SRMs). Advanced SRMs are expected to boost shuttle performance in the early 1990s, but they were not addressed here to avoid confusing their costs with those of the "baseline" shuttle program. Orbiter upweight capacity is about 55,500 lb, with the exception of Columbia (OV-102) which is only 47,100 lb because of its higher dry weight.[15]

[9] M. Robert Seldon, *Life-Cycle Costing: A Better Method of Government Procurement*, Westview Press, Boulder, CO, 1979, p. 57.

[10] "New Briefs," *Aviation Week & Space Technology*, February 29, 1988, p. 34.

[11] Rankine, op. cit.

[12] Blond and Gore, op. cit.

[13] "Pads Available for 18 Delta II Launches per Year," *Aerospace Daily*, July 22, 1987, pp. 459–460.

[14] Blond and Gore, op. cit., and Congressional Budget Office, *Setting Space Transportation Policy for the 1990s*, U.S. Government Printing Office, Washington, D.C., October 1986.

[15] NASA, *Report to the National Research Council on the NASA Space Station Transportation Study*, August 3, 1987.

Table B.1

COST SPREADSHEET FOR TITAN 4

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	[illegible] No Upper Stage				[illegible]							
3	[illegible]				Payload [illegible]		KSC	39[illegible]				
4	[illegible] payload by [illegible]						VAFB	[illegible]500				
5												
6	[illegible]			2/year		4/year		[illegible] year		8/year		
7	[illegible]			9[illegible]		85 [illegible]		8[illegible]		[illegible]5 4		
8	[illegible]		33 [illegible]		[illegible]		25 [illegible]		2[illegible]			
9	[illegible]		[illegible]6 6		[illegible]		[illegible]4 5		[illegible]			
10	[illegible]		3 4		[illegible]4		[illegible]		[illegible]			
11	[illegible]		6 [illegible]		[illegible]		[illegible]		6 [illegible]			
12	[illegible]			43 4		36 [illegible]		[illegible]		24 9		
13	[illegible]		38 5		[illegible]		2[illegible]		2[illegible]			
14	[illegible]		[illegible]		[illegible]		[illegible]		2			
15	[illegible]		2 2		[illegible]		[illegible]		2 [illegible]			
16	[illegible]			[illegible]		22 [illegible]		[illegible]		[illegible]3 3		
17	[illegible]			[illegible]		[illegible]44 7		[illegible]6		[illegible]3 6		
18												
19	[illegible]		Cost/flight = [illegible]	[illegible] flights per year) + [illegible]5.64								
20	No learning											
21												
22	[illegible]			[illegible]	[illegible]	1992	[illegible]	[illegible]4	[illegible]	[illegible]	199[illegible]	[illegible]8
23	[illegible]			[illegible]	[illegible]	9	[illegible]	[illegible]	[illegible]	9	[illegible]	9
24	[illegible] 1988 [illegible]			[illegible]	[illegible]	3[illegible]	40	4[illegible]	[illegible]	6[illegible]	[illegible]6	85
25	[illegible]			[illegible]3 83	95[illegible] 74	950 74	950 74	95[illegible] 74	95[illegible] 74	950 [illegible]	950 74	95[illegible] 74
26	[illegible]											
27	[illegible]		[illegible]5%									
28	[illegible]			640 [illegible]	[illegible]	737 40	723 62	[illegible]2 83	[illegible]	69[illegible] 52	690 05	[illegible]84 [illegible]
29	[illegible]			640 [illegible]5	[illegible]	2[illegible]33 80	2857 4[illegible]	[illegible]57[illegible] 25	42[illegible]4 [illegible]	49[illegible]	5660 8[illegible]	[illegible]345 [illegible]
30		Discount rate	5%									
31	[illegible]		8[illegible]99 [illegible] 1990									
32												
33	[illegible]			[illegible]	[illegible]	35[illegible]900	351900	[illegible]51900	[illegible]51900	351900	351900	[illegible]51900
34	[illegible]											
35	[illegible]			[illegible]	[illegible]	[illegible]38400	[illegible]290[illegible]	[illegible]642000	[illegible]994100	2346000	269[illegible]900	[illegible]049800
36	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]214 54	[illegible]	2[illegible]43 44	2[illegible]8 82	2038 2[illegible]	[illegible]082 52
37	[illegible]											

	M	N	O	P	Q	R	S	T	U	V	W	X
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2004	[illegible]	[illegible]	[illegible]	[illegible]8	[illegible]	[illegible]
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible]	[illegible]	[illegible]	[illegible]4	[illegible]	[illegible]4[illegible]	[illegible]	[illegible]	[illegible]84	[illegible]	2[illegible]8	[illegible]
25	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	98[illegible] 65	[illegible]	[illegible]	[illegible]	[illegible]	98[illegible]5	98[illegible] 65
26												
27												
28	[illegible]	[illegible]	[illegible]	6[illegible] 6[illegible]	[illegible]86 6[illegible]	682 34	6[illegible]8 4[illegible]	[illegible]	[illegible]	[illegible]	665 3[illegible]	662 6[illegible]
29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1045[illegible] 45	[illegible]29 8[illegible]	[illegible]	[illegible]	[illegible]	[illegible]809 [illegible]	[illegible]447[illegible] 39
30												
31												
32												
33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	469[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	469[illegible]	469[illegible]
34												
35	[illegible]	[illegible]	[illegible]	[illegible]	564[illegible]	55[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]859[illegible]	6378[illegible]
36	[illegible]	[illegible]	[illegible]	[illegible]985 [illegible]	[illegible] 82	[illegible]895 [illegible]6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
37												

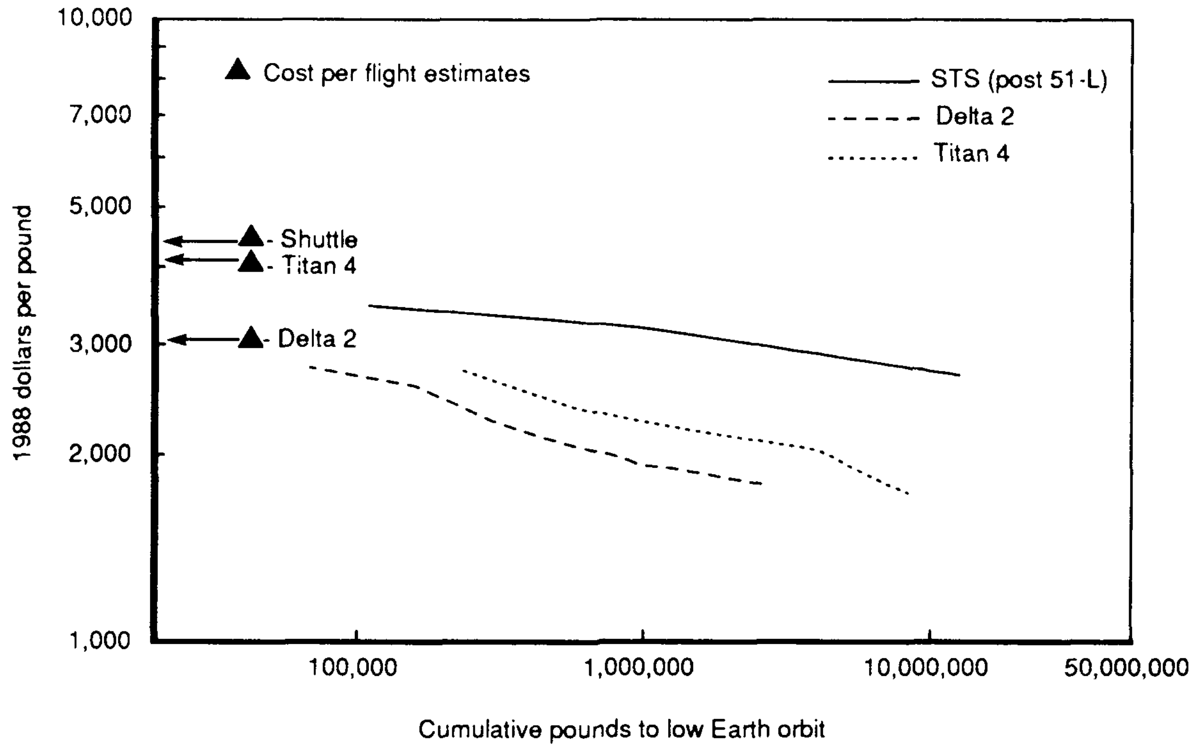


Fig. B.2—Launch costs for existing systems

After initial recovery flights, the STS flight rate was assumed to level off at about 12 per year, consistent with post-Challenger recommendations by the National Research Council.[16] At these planned flight rates, the current orbiters should last through at least 2008, assuming no further losses. A 95 percent Crawford learning curve was assumed for future productivity gains in flight preparation and processing.

A summary spreadsheet is attached as Table B.3. The cumulative amount of mass that could be launched was divided by cumulative costs incurred to obtain an average of cost per pound as a function of payload mass. At a cumulative level of about 12 million pounds (after STS 51-L), the cost per pound could get as low as $2700 per pound. Figure B.2 shows that this is about 60 percent of the current $4400 per pound cost per flight. To the extent production learning occurs, the shuttle cost per flight used in the main text is conservative.

For comparative purposes, historical STS cumulative costs were assessed to see how the shuttle was doing prior to the loss of Challenger. NASA budget data on direct obligations for the STS was separated by major categories such as DDT&E, production, and operations. Additional capability developments such as Spacelab and upper stages were deleted in order to focus on only the cost per payload pound to low Earth orbit.

Through 1986, about $35.8 billion was spent on the STS for access to LEO.[17] Between 1981 and 1986, 24 shuttle flights occurred that were capable of placing about 1.2 million

[16]National Research Council, *Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization*, October 1986.

[17]David Stuart, unpublished manuscript on NASA direct obligations for the Space Shuttle and Saturn launch vehicles, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, October 1986.

Table B.2

COST SPREADSHEET FOR MLV 1 (DELTA 2)

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	Medium Launch Vehicle 1 (Delta 2)				1988$M							
3	No upper stage				Payload (lbs)	to 100 nm =	(KSC)	11400				
4	All flights at KSC						(VAFB)					
5												
6	Flights Year		2 year	4 year	6 year	8 year						
7	Booster hardware		27 6	24 3	23 2	22 1						
8	Payload fairing		1 1	1 1	1 1	1 1						
9	Launch Support		14 4	9	6 7	5.6						
10	Govt Services		4 7	2 3	1 3	1.3						
11	Range Operations		2 2	2 2	2 2	2 2						
12	Other Govt costs		3 3	3 3	3 3	3 3						
13	Total Cost flight		53 3	42 2	37 8	35 6						
14												
15	Linear Regression		Cost flight =	1 711*(flights	per year)+48 8							
16	No learning											
17												
18	Fiscal Year			1990	1991	1992	1993	1994	1995	1996	1997	1998
19	Flights year			6	8	12	12	12	12	12	12	12
20	Cum Flights (9 in 1988 89)			15	23	35	47	59	71	83	95	107
21	Annual Costs (no learning) =			231 20	280 90	339 22	339 22	339.22	339 22	339 22	339 22	339 22
22	Insurance Costs =											
23	Learning curve =		95%									
24	Annual Cost (with learning) =			189 22	222 73	260 74	255 12	250 86	247 45	244 60	242 17	240 05
25	Cum costs			189 22	411 95	672 69	927 81	1178 67	1426 12	1670 72	1912 89	2152 94
26		Discount rate =	5%									
27	Net Present Costs =		3014 64	(to 1990)								
28												
29	Total Ann. Pounds to Leo =			68400	91200	136800	136800	136800	136800	136800	136800	136800
30	(al launchs from KSC)											
31	Cum Pounds to Leo =			68400	159600	296400	433200	570000	706800	843600	980400	1117200
32	$/Lb (running average) =			2766 35	2581 13	2269.54	2141 75	2067 84	2017 71	1960 47	1951 13	1927 09
33	undiscounted											

	M	N	O	P	Q	R	S	T	U	V	W	X
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
19	12	12	12	12	12	12	12	12	12	12	12	12
20	119	131	143	155	167	179	191	203	215	227	239	251
21	339 22	339 22	339 22	339 22	339 22	339 22	339 22	339 22	339 22	339 22	339 22	339 22
22												
23												
24	238 1[illegible]	236 48	234 95	233 56	232 2[illegible]	231 08	229 97	228 94	227 97	227 05	226 19	225 37
25	2391 1[illegible]	2627 59	2862 54	3096 10	3328 37	3559 45	3789 43	4018 36	4246 33	4473 39	4699 58	4924 95
26												
27												
28												
29	136800	136800	136800	136800	136800	136800	136800	136800	136800	136800	136800	136800
30												
31	1254000	1390800	1527600	1664400	1801200	1938000	2074800	2211600	2348400	2485200	2622000	2758800
32	1926 79	1889 27	1873 88	1860 1[illegible]	1847 66	1836 66	1826 41	1816 95	1808 18	1800 01	1792 36	1785 18
33												

Table B.3

COST SPREADHSEET FOR CURRENT SHUTTLE

	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2	Shuttle Cost per Flight				1988M$	AFSD Estimates							
3	All flights from KSC												
4													
5	Materials & Services			102.10									
6	Solid Rocket Booster		42.04										
7	Expendable Tank		33.19										
8	Orbiter Hardware Spares		15.38										
9	Crew Equipment		3.87										
10	SSMEs		5.20										
11	Contract Administration		2.43										
12													
13	Flight Operations Support			51.98									
14	Flight Operations		38.16										
15	Network Support		4.31										
16	R&PM		9.51										
17													
18	KSC Launch Operations Support			48.78									
19	Launch Operations		36.17										
20	Propellants		1.33										
21	GSE Spares		2.21										
22	R&PM		9.07										
23													
24	Cost/Launch @ KSC			202.86									
25	Short-run additive cost		DDT&E sunk, no capital amortization, expansion										
26			STS 51-L recovery costs sunk			104% SSMEs, No ASRMs							
27	(OV-099 lost after 9 flights)												
28	(15 flights by other Orbiters)			1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
29	Flights/Year Total			2	7	9	9	12	12	12	12	12	12
30	STS Cum. Flights (post-51L)			2	9	18	27	39	51	63	75	87	99
31		Up-Weight (28.5,110 nm)											
32	OV-102	47100		0	2	3	2	2	2	2	2	2	2
33	Cum. flights to date			7	9	12	14	16	18	20	22	24	26
34	OV-103	55500		1	2	3	3	3	3	3	3	3	3
35	Cum. flights to date			7	9	12	15	18	21	24	27	30	33
36	OV-104	55500		1	3	3	3	4	3	3	3	3	3
37	Cum. flights to date			3	6	9	12	16	19	22	25	28	31
38	OV-105	55500		0	0	0	1	3	4	4	4	4	4
39	Cum. flights to date			0	0	0	1	4	8	12	16	20	24
40													
41	lbs./year			111000	371700	474300	482700	649200	649200	649200	649200	649200	649200
42	Cum. Pounds to orbit after 51-L			111000	482700	957000	1439700	2088900	2738100	3387300	4036500	4685700	5334900
43	Learning Curve (Crawford) =		95%										
44	Discount rate=	5%											
45													
46	Cost per flight =			192.72	172.42	163.80	158.96	154.69	151.65	149.30	147.38	145.77	144.39
47	Annual Costs =			385.44	1206.94	1474.19	1430.61	1856.28	1819.79	1791.56	1768.59	1749.27	1732.62
48	Cum. Costs =			385.44	1592.38	3066.56	4497.18	6353.45	8173.24	9964.80	11733.39	13482.66	15215.28
49	Net Present Cost =		19911.09										
50	Cum. Cost (undiscounted) =		33556.32										
51	$/lb (undiscounted) =			3472.42	3298.89	3204.35	3123.69	3041.53	2985.01	2941.81	2906.82	2877.41	2852.03

Table B.3—(Continued)

	N	O	P	Q	R	S	T	U	V	W	X
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											
21											
22											
23											
24											
25											
26											
27											
28	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
29	12	12	12	12	12	12	12	12	12	12	12
30	111	123	135	147	159	171	183	195	207	219	231
31											
32	2	2	2	2	2	2	2	2	2	2	2
33	28	30	32	34	36	38	40	42	44	46	48
34	3	3	3	3	3	3	3	3	3	3	3
35	36	39	42	45	48	51	54	57	60	63	66
36	3	3	3	3	3	3	3	3	3	3	3
37	34	37	40	43	46	49	52	55	58	61	64
38	4	4	4	4	4	4	4	4	4	4	4
39	28	32	36	40	44	48	52	56	60	64	68
40											
41	649200	649200	649200	649200	649200	649200	649200	649200	649200	649200	649200
42	5984100	6633300	7282500	7931700	8580900	9230100	9879300	10528500	11177700	11826900	12476100
43											
44											
45											
46	143.17	142.08	141.11	140.22	139.41	138.66	137.97	137.32	136.72	136.15	135.61
47	1718.02	1705.02	1693.31	1682.67	1672.93	1663.95	1655.62	1647.85	1640.59	1633.76	1627.32
48	16933.30	18638.31	20331.63	22014.30	23687.23	25351.18	27006.79	28654.65	30295.23	31928.99	33556.32
49											
50											
51	2829.72	2809.81	2791.85	2775.48	2760.46	2746.58	2733.67	2721.63	2710.33	2699.69	2689.65

pounds into the reference orbit. A summary spreadsheet (Table B.4) covers shuttle flights and STS costs between 1970 and 1986. It is difficult to say what the cost per pound numbers mean in this case save that the investments made were being amortized and costs coming down before the loss of STS 51-L. As shown in Fig. B.3, the full STS cost per pound could be placed as $28,000 prior to the accident.

B.7 SATURN V

The Saturn V program can provide historical launch vehicle costs for comparison with current heavy-lift vehicle plans. The Saturn V's payload capability was about 280,000 lb to the reference orbit and it flew 11 times between 1968 and 1973. Although its development depended directly on the prior efforts of the Saturn I and IB, it is possible to separate out direct obligation due to the Saturn V itself. For the period 1961 to 1973, about $25.4 billion was spent on the Saturn V.[18]

A summary spreadsheet (Table B.5) shows the above information in more detail. With the same caveats as for historical shuttle costs, the cost per pound at the end of the program was down to $8200. As shown in Fig. B.3, the slope of the Saturn V's cost amortization was similar to that of the shuttle. The Saturn's amortization rate was slightly faster due to its greater payload capacity whereas the shuttle had capabilities other than payload weight beyond those of Saturn. The shuttle's curve ends in 1986 with the STS 51-L accident; Saturn terminated with the end of the Apollo and Skylab programs.

B.8 ADVANCED LAUNCH SYSTEM

The Advanced Launch System (ALS) is a family of launch vehicles being developed by the Air Force for an initial operating capability date of 1998. Figure B.4 shows several ALS vehicles that could cover a wide range of payload weight and volume requirements. Early plans had called for an interim vehicle available by 1993–1994, but this option was dropped in 1987.[19] The ALS includes a heavy-lift vehicle capable of placing at least 100,000 lb into LEO, and more importantly, lower operating costs to orbit by a factor of 10 over current practices (commonly cited as the Titan 34D at about $3600 per pound).[20]

There are several design approaches for ALS vehicles. Some designs require a major technology development effort. Others are based on current technologies with changes in ground processing and vehicle production lines making the largest contribution to cost reductions. There is some concern in the Air Force payload community which feels that they may have to pay for or provide services that were provided by the vehicle in the past. This has led to concern about reducing vehicle costs at the expense of increasing payload costs.

Rockwell International has provided an example of a fully expendable ALS vehicle design using existing technologies and J-2S engines from the Saturn program.[21] The design had a three-year build time after a five-year DDT&E effort starting in 1994. New facilities were to be built at KSC and VAFB resulting in a total nonrecurring cost (including DDT&E) of about $4.9 billion. The mature flight rate was assumed to be 21 per year, comprised of 15 flights from KSC and six from VAFB. Its payload was 150,000 pounds to the reference orbit.

Given the new nature of the ALS, a slightly higher learning curve of 90 percent was assumed relative to established systems. If all costs are included, the cost per pound could drop to $1200 at a cumulative payload mass to orbit of 33 million pounds. If nonrecurring

[18]Ibid.

[19]See Sec. 2.4.

[20]U.S. Congress, "National Defense Authorization Act for Fiscal Years 1988 and 1989, H.R. 1748, Section 256, Advanced Launch System," *Congressional Record—House*, H10134, November 17, 1987.

[21]Interview with W. McClure, Rockwell International, December 1987.

Table B.4

COST SPREADSHEET FOR HISTORICAL SHUTTLE

	A	B	C	D	E	F	G	H	I	J	K
1											
2	Direct Shuttle Costs										
3	Source NASA budget estimates, Dave Stuart (MIT)										
4	Direct Obligations										
5	*Current $*			Totals	1970	1971	1972	1973	1974	1975	1976
6											
7	DDT&E			1 0092E+10	12500000	78500000	100000000	198575000	475000000	797500000	1206000000
8	Production			2257200000							
9	*Shuttle Production*										
10	and Operational Capability			4654860000							
11	STS Operations Capability Development										
12	(Spacelab, IUS, etc)		(deleted)	0							
13	STS Operations			452300000							
14	Shuttle Operations			3176000000							
15				0							
16	Total			2 0633E+10	12500000	78500000	100000000	198575000	475000000	797500000	1206000000
17											
18	GNP deflators to 88$				0 283	0 294	0 307	0 345	0 419	0 473	0 502
19	Ann Costs				44169611	267006803	325732899	575579710	1133651551	1686046512	2402390438
20	Cum Costs =				44169611	311176414	636909313	1212489023	2346140575	4032187086	6434577524
21	Total Cost =	3 5796E+10		Upweight lbs to							
22			Total to 51-L	28 5, 110 nm	1970	1971	1972	1973	1974	1975	1976
23	Flights/year		24								
24	OV 102	Columbia	7	47100							
25	OV 099	Challenger	9	55500							
26	OV 103	Discovery	6	55500							
27	OV 104	Atlantis	2	55500							
28											
29	Ann lbs to Leo										
30	Cum lbs to Leo		1273200								
31											
32	Running average $/lb (undiscounted) =										

	L	M	N	O	P	Q	R	S	T	U	V
1											
2											
3											
4										Budget Authority Numbers	
5	Tr Qtr	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
6											
7	321000000	1343100000	1307500000	1270300000	1115500000	973000000	894000000				
8		70000000	41700000	368000000	755500000	1022000000					
9											
10							1282750000	1725810000	1646300000	1484500000	971600000
11											
12											
13			16500000	24300000	148100000	263400000					
14							435300000	1338700000	1402000000	1314000000	1725000000
15											
16	321000000	1413100000	1365700000	1662600000	2019100000	2258400000	2612050000	3064510000	3048300000	2798500000	2696600000
17											
18	0 518	0 533	0 576	0 651	0 755	0 841	0 872	0 885	0 904	0 907	0 933
19	619691120	2651219512	2371006944	2553917051	2674304636	2685374554	2995470183	3462723164	3372013274	3085446527	2890246517
20	7054268644	9705488156	1 2076E+10	1 463E+10	1 7305E+10	1 999E+10	2 2986E+10	2 6448E+10	2 982E+10	3 2906E+10	3 5796E+10
21											
22	Tr Qtr	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
23						1	3	4	5	8	3
24						1	3	1	1		1
25								3	3	2	1
26									1	5	
27										1	1
28											
29						47100	141300	213600	269100	444000	158100
30						47100	188400	402000	671100	1115100	1273200
31											
32						424418 075	122004 042	65791 753	44434 9545	29509 2319	28114 9788

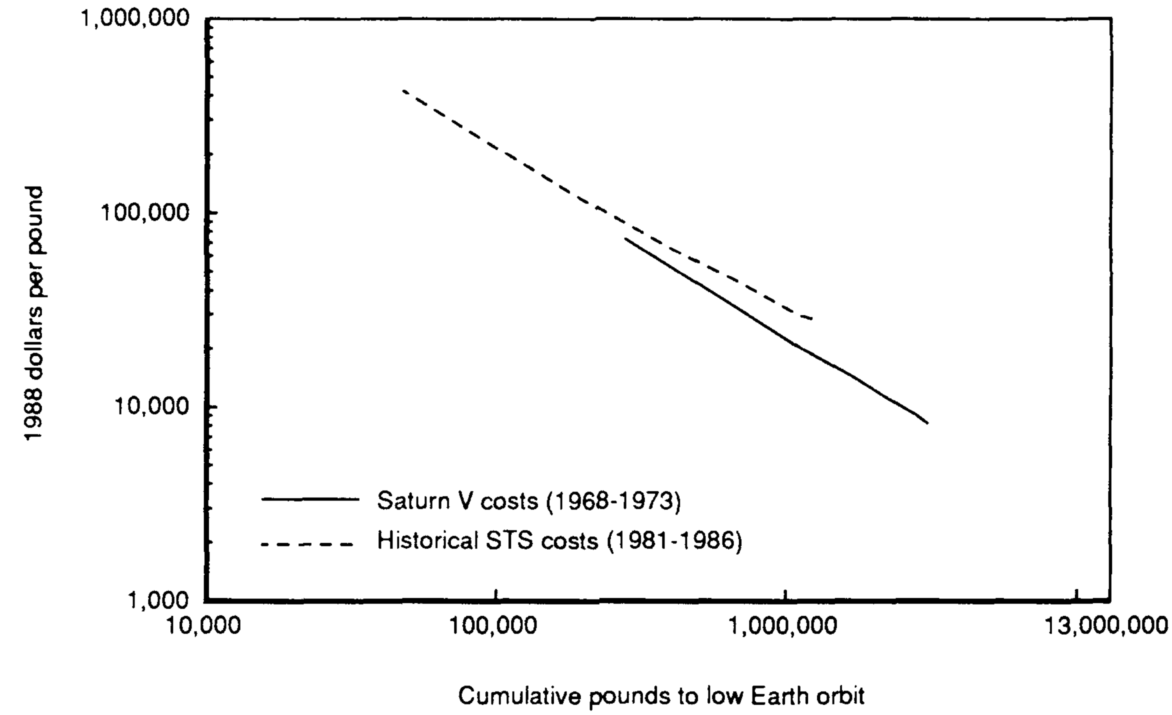


Fig. B.3—Costs to low Earth orbit for historical STS and Saturn V

costs are regarded as sunk, and only production and operations costs are included, the cost per pound could drop as low as $1000 (see Fig. B.5). This cumulative payload mass is reached only in the case of expanded DoD demand levels (see Sec. 4.3.4), the highest traffic level evaluated. A summary spreadsheet is given in Table B.6.

Figure B.5 covers an expendable Advanced Launch System capable of 150,000 lb to LEO. Although it has a higher DDT&E than the Shuttle-C, its projected lower operating costs allow its cost per pound to drop below $3000 after two years, and below $2000 after four years (about 2002). Final cost figures could ' ɘl off at just above a $1000 per pound. Deleting the DDT&E costs helps to increase the . ɹe of c ›st decline. Still, it appears unlikely that this system could go below $1000 per pound.

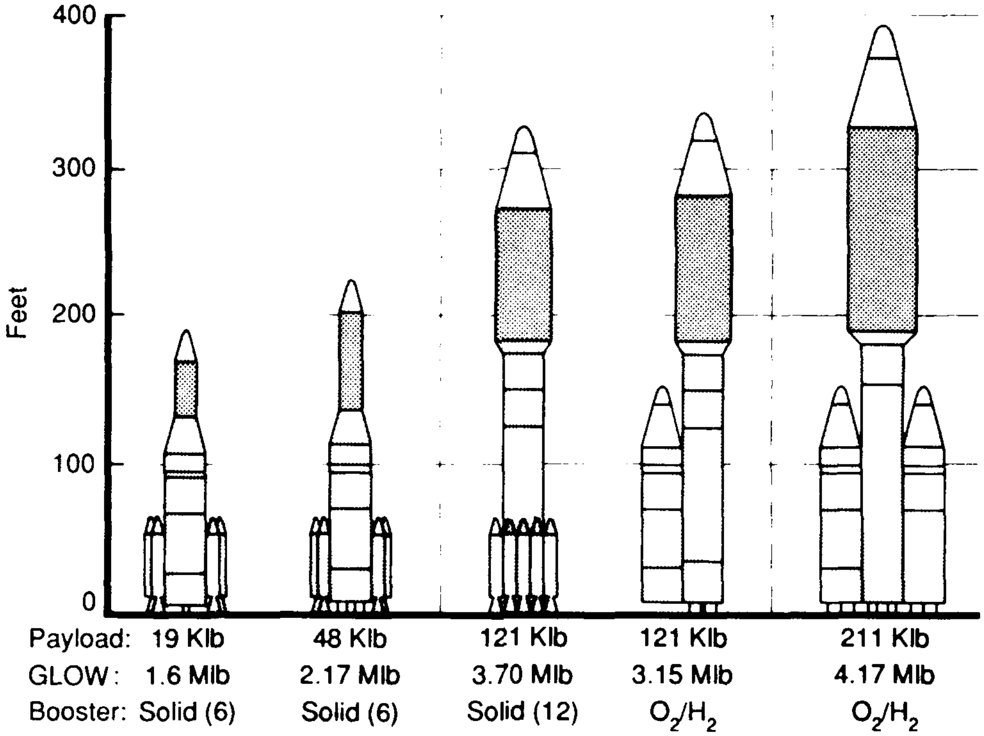
ALS Phase II contracts were awarded in August 1988 to a Martin-Marietta/McDonnell-Douglas team, Boeing, and General Dynamics. Each of the winning companies proposed the use of some reusable elements as opposed to the fully expendable design example discussed above. In its report to the Congress, *Launch Options for the Future: A Buyer's Guide*, the Office of Technology Assessment used the following assumptions for ALS costs.[22] DDT&E costs were estimated to be $9.5 billion, spread over six years and ending before the first launch. Facilities were estimated to cost $150 million times the peak flight rate, spread over four years, and ending before the capability is required. Production costs for reusable elements (primarily avionics and recoverable boosters) were $1.7 billion, spread over five

[22]Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383, U.S. Government Printing Office, Washington, D.C., July 1988, p. 82.

Table B.5

COST SPREADSHEET FOR SATURN V

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1																
2	Saturn V costs		Current $		Data from Dave Stuart, MIT											
3	engine development done under Saturn I and IB															
4																
5			Fiscal Year	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
6	S-IC stage				22575000	129388000	256816000									
7	1st stage (S-IC)							243137000	191906000	158866000	121428000					
8	Dev. eng. Second stage			312000												
9	Flight and exp. hardware Second stage			311000												
10	S-II stage				19284000	95088000	165189000									
11	2nd stage (S-II)							190192000	256164000	249000000	205156000					
12	S-IVB stage				2500000	51359000	135730000									
13	3rd stage (S-IVB)							130300000	162016000	142114000	121825000					
14		Flight stages										402057000		161205000		
15	Vehicle instrument unit					12045000	54522000	74900000								
16	Instrument unit								67760000	72008000	62642000					
17	Guidance system				2590000											
18	Ground Support Equipment					6425000	16281000	63254000	107572000	44854000	38974000					
19	F-1 engine procurement				3400000	14601000	41000000	68100000								
20	F-1 engines								66200000	77434000	81368000					
21	J-2 engine procurement				1200000	14450000	29150000	57965000								
22	J-2 engines								67200000	86731000	71824000					
23	Support				326000											
24	Vehicle support					20086000	64694000	137076000	216053000	267147000	150748000	133653000				
25	Ground support													27854000		
26	Saturn V												486691000		157996000	
27																
28	Ann. totals			623000	57375000	343442000	763382000	964924000	1134871000	1098154000	853965000	535710000	486691000	189059000	157996000	0
29	Pgm. total (current $)		6586192000													
30	Conversion factors to 88$			0.244	0.244	0.244	0.244	0.248	0.256	0.258	0.263	0.273	0.283	0.294	0.307	0.345
31	Ann. total in 88m$			2.55	235.14	1407.55	3128.61	3890.82	4433.09	4256.41	3247.02	1962.31	1719.76	643.06	514.64	0.00
32	Cum. total ($88m)			2.55	237.70	1645.25	4773.86	8664.68	13097.77	17354.18	20601.20	22563.51	24283.26	24926.32	25440.97	25440.97
33	Pgm. total ($88M)		25440.97													
34																
35	Payload (lbs.) to LEO, 28.5, [illegible]nm			280000												
36		Fiscal Year		1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
37											Apollo # 1					Skylab
38	Operational flights/year										1	3	2	2	2	
39	Ann. Payload to orbit			0	0	0	0	0	0	0	280000	840000	560000	560000	560000	280000
40	Cum. Payload to Orbit			0	0	0	0	0	0	0	280000	1120000	1680000	2240000	2800000	3080000
41	$/lb (running average)			#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	73575.71	20145.99	14454.32	11127.82	9086.06	8260.05
42	(in 88$)															



SOURCE: U.S. Air Force and NASA.

Fig. B.4—Advanced launch system

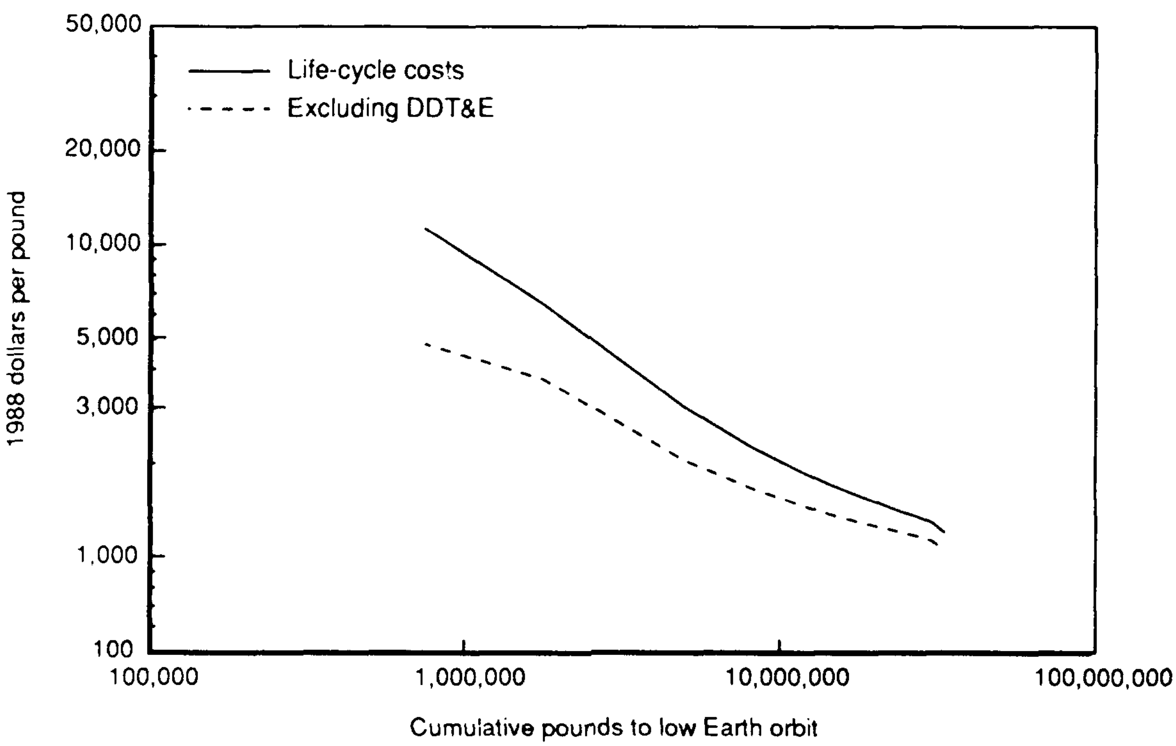


Fig. B.5—Launch costs for Advanced Launch System (expendable)

Table B.6

COST SPREADSHEET FOR ADVANCED LAUNCH SYSTEM (EXPENDABLE)

	A	B	C	D	E	F	G	H	I	J	K	L
1	Advanced Launch System		1988M$	Discount rate =	5.00%							
2	Payload (lbs) to Leo =		150000									
3				1	2	3	4	5	6	7	8	9
4	Fiscal Year		Total	1989	1990	1991	1992	1993	1994	1995	1996	1997
5	DDT&E		2415						232	618	783	580
6	SRM	552.3										
7	Core	818.5										
8	J 2 Engines	398.3										
9	P L Shroud	237.5										
10	IAT	94.6										
11	S W Develop	165										
12	Flt Test	149.2										
13	Facilities KSC		1034.3					67.4	326	416.1	224.8	
14	LCC	51.2										
15	Core Station	40.5										
16	Booster Sta	0										
17	P L Integ	85.6										
18	SRM Sta	14.5										
19	VIB Cell	109.4										
20	PAD	564.8										
21	MLP Crawler	134.4										
22	Storage Sta	33.9										
23	Facilities VAFB		1436.6					94.1	455.1	573.4	314	
24	LCC											
25	Core Station											
26	Booster Sta											
27	P L Integ											
28	SRM Station											
29	VIB Cell											
30	PAD											
31	MLP Crawler											
32	Storage Sta											
33												
34	Non recurring costs =		4885.9	0	0	0	0	161.5	1013.1	1607.5	1321.8	580
35												
36	Annual Flights											
37	KSC											

	M	N	O	P	Q	R	S	T	U	V	W	X
1												
2												
3	10	11	12	13	14	15	16	17	18	19	20	21
4	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
5	202											
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												
24												
25												
26												
27												
28												
29												
30												
31												
32												
33												
34	202	[illegible]	0	0	0	0					0	
35												
36	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
37	[illegible]	[illegible]	[illegible]	[illegible]	15	15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table B.6—(continued)

	A	B	C	D	E	F	G	H	I	J	K	L
38	VAFB											
39	Cum Flights											
40	KSC											
41	VAFB											
42	TFU Vehicle (all expendable)		275									
43	3 year build time, 20/50/30 ogive											
44	Booster		53 1									
45	SRM	17 1										
46	SRB	30 4										
47	IACO	5 6										
48	Engines		4 3									
49	Airframe		120 5									
50	Core IACO		1 8									
51	P/L Shroud		2 9									
52	Vehicle IACO		11 4									
53	Learning Curve (Wright) =		90%									
54	Prod Lot No	No in Lot	Vehicle Cost	Cum Prod	Lot Cost							
55	1	5	275	5	1375 00						275 00	687 50
56	2	7	188 49	12	1319 45							263 89
57	3	21	161 63	33	3394 17							
58	4	21	149 97	54	3149 36							
59	5	21	142 67	75	2995 97							
60	6	21	137 41	96	2885 63							
61	7	21	133 34	117	2800 15							
62	8	21	130 04	138	2730 76							
63	9	21	127 27	159	2672 59							
64	10	21	124 89	180	2622 67							
65	11	21	122 81	201	2579 05							
66	12	21	120 97	222	2540 38							
67												
68	Production Costs =						0 00	0 00	0 00	0 00	275 00	951 39
69	Flight Operations Costs =			85 5								85 5
70	Mission Planning		9									
71	Mission Design		18 4									
72	Training		5									
73	Real time Support		5 4									
74	Post flight		1 2									

	M	N	O	P	Q	R	S	T	U	V	W	X
38	2	2	6	6	6	6	6	6	6	6	6	6
39	5	12	33	54	75	96	117	138	159	180	201	222
40	3	8	23	38	53	68	83	98	113	128	143	158
41	2	4	10	16	22	28	34	40	46	52	58	64
42												
43												
44												
45												
46												
47												
48												
49												
50												
51												
52												
53												
54												
55	412 50											
56	659 72	395 83										
57	678 83	1697 08	1018 25									
58		629 87	1574 68	944 81								
59			599 19	1497 98	898 79							
60				577 13	1442 81	865 69						
61					560 03	1400 08	840 05					
62						546 15	1365 38	819 23				
63							534 52	1336 30	801 78			
64								524 53	1311 33	786 80		
65									515 81	1289 52	773 71	
66										508 08	1270 19	762 11
67												
68	1751 06	2722 79	3192 12	3019 92	2901 63	2811 92	2739 94	2680 06	2628 92	2584 40	2043 90	762 11
69	85 5	85 5	85 5	85 5	85 5	85 5	85 5	85 5	85 5	85 5	85 5	85 5
70												
71												
72												
73												
74												

Table B.6—(continued)

	A	B	C	D	E	F	G	H	I	J	K	L
75	Network Support		46 5									
76	No split between KSC and VAFB											
77	KSC Launch Ops =			94 1								94 1
78	Propellant Systems		8 6									
79	GSE Spares		6 6									
80	Launch Processing		9 3									
81	O&M/Base Support		69 6									
82	VAFB Launch Ops =			115 3								115 3
83	Propellant Systems		3 5									
84	GSE Spares		9 2									
85	Launch Processing		5 5									
86	O&M/Base Support		97 1									
87	Overall Wrap costs =		10%									
88	Total Ops Costs (plus wrap)			324 39	0	0	0	0	0	0	0	324 39
89												
90	Total Ann Costs =				0 00	0 00	0 00	161 50	1013 10	1607 50	1596 80	1855 78
91	Total Cum Costs =				0	0 00	0 00	161 50	1174 60	2782 10	4378 90	6234 68
92	Insurance Costs =											
93												
94	Disc Total Ann Costs =				0 00	0 00	0 00	132 87	793 79	1199 54	1134 82	1256 06
95	Disc Cum Costs =				0	0 00	0 00	132 87	926 66	2126 20	3261 01	4517 08
96												
97	Total Ann [illegible]ds to Leo =				0	0	0	0	0	0	0	0
98	Total Cum Pounds to Leo =				0	0	0	0	0	0	0	0
99												
100	Dollars/lb (LCC average) =				#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
101	Dollars/lb (Disc LCC average) =				#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
102												
103	Production + Ops Costs =				0 00	0 00	0 00	0 00	0 00	0 00	275 00	1275 78
104	Cum Prod + Ops Costs =				0	0 00	0 00	0 00	0 00	0 00	275 00	1550 78
105	Dollars/lb (less non recurring)				#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
106	running average, undiscounted											

	M	N	O	P	Q	R	S	T	U	V	W	X
75												
76												
77	94 1	94 1	94 1	94 1	94 1	94 1	94 1	94 1	94 1	94 1	94 1	94 1
78												
79												
80												
81												
82	115 3	115 3	115 3	115 3	115 3	115 3	115 3	115 3	115 3	115 3	115 3	115 3
83												
84												
85												
86												
87												
88	324 39	324 39	324 39	324 39	324 39	324 39	324 39	324 39	324 39	324 39	324 39	324 39
89												
90	[illegible]	3041 18	3516 51	3344 31	3226 02	3136 31	3064 33	3004 45	2953 31	2908 79	2368 29	1086 50
91	8512 13	11559 31	15075 82	18420 13	21646 15	24782 46	27846 79	30851 24	33804 56	36713 35	39081 64	40168 15
92												
93												
94	1468 06	1870 70	2056 03	1862 24	1710 83	1584 05	1474 00	1376 37	1288 52	1208 66	937 21	409 49
95	5985 14	7855 85	9911 88	11774 11	13484 94	15068 99	16542 99	17919 36	19207 88	20416 54	21353 76	21763 25
96												
97	750000	1050000	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000
98	750000	1800000	4950000	8100000	11250000	14400000	17550000	20700000	23850000	27000000	30150000	33300000
99												
100	11349 50	6421 84	3045 62	2274 09	1924 10	1721 00	1586 71	1490 40	1417 38	1359 75	1296 24	1206 25
101	7980 19	4364 36	2002 40	1453 59	1198 66	1046 46	942 62	865 67	805 36	756 17	708 25	653 55
102												
103	[illegible]	3041 18	3516 51	3344 31	3226 02	3136 31	3064 33	3004 45	[illegible]	2908 79	2368 29	1086 50
104	3626 23	6673 41	10189 92	[illegible]	[illegible]	19896 56	22960 89	25965 34	28918 66	31827 45	34195 74	35282 25
105	[illegible]	[illegible]	2058 57	1670 89	1489 80	1381 71	1308 31	1254 36	1212 52	1178 79	1134 19	1059 53
106												

years. Fixed operations costs were estimated to be $241 million per year, independent of the flight rate. Variable operations costs were estimated to be $33 million per flight, which included all expendables. No learning curves were assumed.

The OTA cost estimates were used with the same flight rate assumptions as the Rockwell expendable design (see the cost spreadsheet in Table B.7). Figure B.6 shows how the average cost per pound drops as a function of cumulative mass placed in orbit. If all costs are included, the OTA estimates would show a cost per pound under $800 at a cumulative level of 33 million pounds. If DDT&E costs are neglected, the cost per pound could drop to less than $500. This may be due to the use of reusable elements as well as more favorable cost assumptions.

The OTA numbers are slightly lower than those for the fully expendable design, but it is difficult to say which is more realistic. Given that the OTA numbers reflect the more recent decisions of the ALS program (as compared to the expendable vehicle design), their estimates were used in the main text as the ALS cost assumptions. It should be stressed that these results depend on many assumptions and do not take into account potential cost impacts on the payloads. Although the costs shown above are significant improvements over existing vehicles, the goal of $300 per pound, as stressed in Congressional legislation, seems unrealistic given current technology and cost estimating assumptions.[23]

B.9 SHUTTLE-C

An alternative to the ALS for heavy-lift launches could be the NASA proposal to build an unmanned cargo vehicle from shuttle hardware. The orbiter would be replaced with a cargo element that also contained shuttle main engines. This configuration could provide a capability of about 120,000 lb to the reference orbit. DDT&E has been estimated at about $1.2 billion over six years, with first flight in 1994.[24] Figure B.7 is a view of an example Shuttle-C design by Martin Marietta.

A total production run of 30 vehicles over 11 years was assumed, allowing for a steady rate of three Shuttle-C flights per year. Again, because of its new nature (despite a high degree of inheritance from the shuttle), a 90 percent learning curve was assumed in production. Production time per vehicle was assumed to be four years with an initial operating cost of $120 million per flight (including launch operations, flight operations, NASA support, and costs of using STS facilities).[25] A summary spreadsheet appears as Table B.8.

Figure B.8 shows how the Shuttle-C cost per pound would drop as cumulative mass launched increased. If all costs are included, costs per pound could drop to $4400 at cumulative payload mass levels of 3.6 million pounds. This level of payload mass would be reached in the case of expanded civil demand (see Sec. 4.3.3). If DDT&E costs are treated as sunk, the cost per pound would only drop to about $4100. Deleting the DDT&E does not help much as it is already relatively small (~$1.2 billion). The Shuttle-C does not incorporate any reusable hardware, so its operating costs are above those of the shuttle.

Figure B.9 compares the cost per pound behavior of the Shuttle-C and ALS, with the latter using the OTA cost estimates. The figure shows the ALS is considerably cheaper and capable of greater payload than the Shuttle-C. The Shuttle-C, however, could be available earlier, which may be useful for missions such as space station deployment and support.

[23]U.S. Congress, op. cit.

[24]Rockwell International, *Definition of a Space Transportation System Cargo Element*, DR-2, Downey, CA, February 10, 1988; Martin-Marietta, *Definition of a Space Transportation System Cargo Element*, DR-2, Denver, CO, February 1988; and United Technologies, *Performance Review of Shuttle-C Definition Study*, DR-2, Huntsville, AL, January 15, 1988.

[25]Ibid.

Table B.7

COST SPREADSHEET FOR ADVANCED LAUNCH SYSTEM (OTA)

	A	B	C	D	E	F	G	H	I	J	K
1	Advanced Launch System		OTA Launch Vehicles Buyer's Guide Cost Estimates								
2			1988M$		Facilities cost equals $150M times peak flight rate						
3	Payload to LEO	150000									
4	Fiscal Year	Subtotal	1	2	3	4	5	6	7	8	9
5			1992	1993	1994	1995	1996	1997	1998	1999	2000
6	Flight Rate								5	7	21
7	Mass/year		0	0	0	0	0	0	750000	1050000	3150000
8	Cum. Mass		0	0	0	0	0	0	750000	1800000	4950000
9											
10	DDT&E	9500	950	1900	1900	1900	1900	950			
11	Prod. Costs	1700		255	340	340	510	255			
12	Facilities	3150					787.5	787.5	787.5	787.5	
13	Facilities	0									
14	Fixed Ops. Costs = 241/year								241	241	241
15	Variable Ops Cost = 33/flight								165	231	693
16											
17	Cost per year		950	2155	2240	2240	3197.5	1992.5	1193.5	1259.5	934
18	Cum. cost		950	3105	5345	7585	10782.5	12775	13968.5	15228	16162
19	Cum Cost/lb.								18625	8460	3265
20											
21	Cost per year (no DDT&E)		0	255	340	340	1297.5	1042.5	1193.5	1259.5	934
22	Cum. cost		0	255	595	935	2232.5	3275	4468.5	5728	6662
23	Cum Cost/lb. (no DDT&E)								5958	3182	1346
24											
25	Cum. Mass		0	0	0	0	0	0	750000	1800000	4950000
26	Cum Cost/lb.								18625	8460	3265
27	Cum Cost/lb (no DDT&E)								5958	3182	1346

	L	M	N	O	P	Q	R	S	T	U
1										
2										
3										
4	10	11	12	13	14	15	16	17	18	19
5	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
6	21	21	21	21	21	21	21	21	21	21
7	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000	3150000
8	8100000	11250000	14400000	17550000	20700000	23850000	27000000	30150000	33300000	36450000
9										
10										
11										
12										
13										
14	241	241	241	241	241	241	241	241	241	241
15	693	693	693	693	693	693	693	693	693	693
16										
17	934	934	934	934	934	934	934	934	934	934
18	17096	18030	18964	19898	20832	21766	22700	23634	24568	25502
19	2111	1603	1317	1134	1006	913	841	784	738	700
20										
21	934	934	934	934	934	934	934	934	934	934
22	7596	8530	9464	10398	11332	12266	13200	14134	15068	16002
23	938	758	657	592	547	514	489	469	452	439
24										
25	8100000	11250000	14400000	17550000	20700000	23850000	27000000	30150000	33300000	36450000
26	2111	1603	1317	1134	1006	913	841	784	738	700
27	938	758	657	592	547	514	489	469	452	439

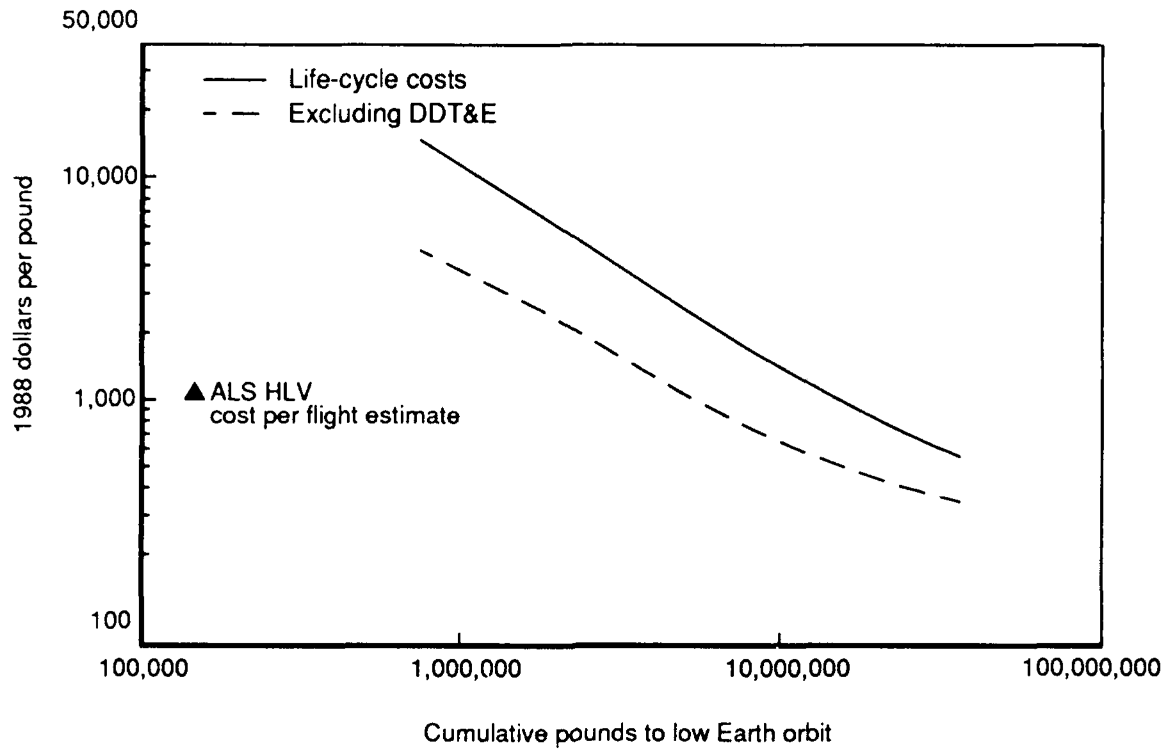


Fig. B.6—Launch costs for Advanced Launch System (OTA)

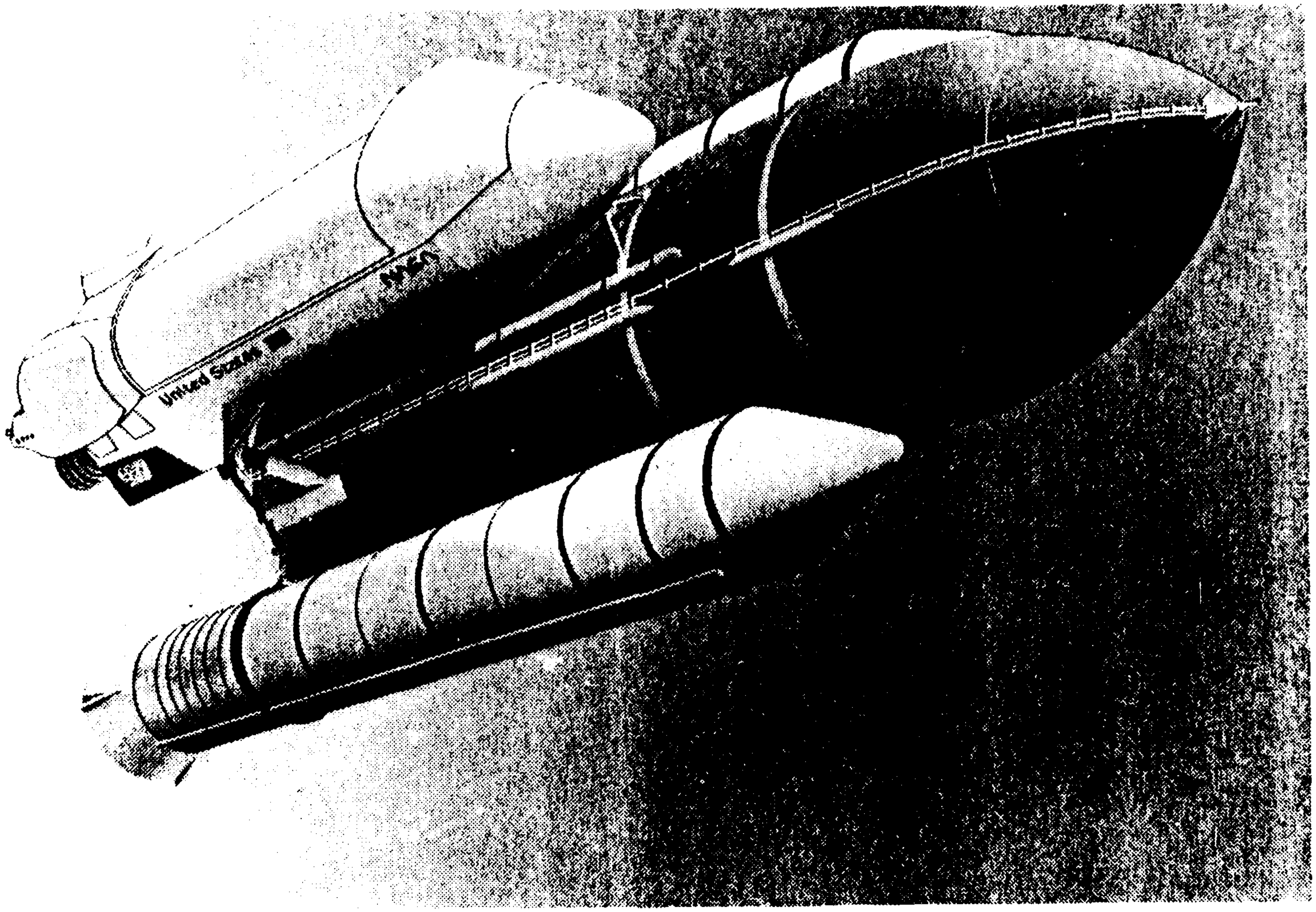
B.10 CONCLUSIONS

Figure B.10 summarizes the launch vehicle cost projections discussed in this appendix. The estimates for recurring costs per flight, used in the main text, are also shown compared with the more general behavior of costs as a function of cumulative payload mass. The estimates are conservative with respect to the projections for current vehicles. For potential vehicles, such as the Shuttle-C and ALS, the cost per flight point estimates are comparable to the levels reached after nonrecurring costs have been amortized (as was assumed for current vehicles). This gives the benefit of the doubt to potential vehicles in terms of meeting their operational goals.

As the ALS approaches 10 million pounds placed in orbit, it could be less expensive than using the shuttle or Titan 4 and Delta 2. The comparison can be misleading, however, as the ALS payload capacity is so large that its payloads are likely to be very different from those flown on current vehicles. In addition, there has been no adjustment for the difference in risks borne by payloads flying a new vehicle versus ones with many more years of experience.

In general, costs drop with greater mass placed in orbit due to two factors: (1) the spreading of fixed costs over a greater number of pounds and (2) learning curve effects that bring down the unit cost of each production vehicle. Current vehicles have their DDT&E sunk today, whereas proposed vehicles are charged for that cost. To some degree, this favors using current vehicles over developing new ones on a cost basis alone.

New vehicles have a difficult challenge in improving on current costs per pound. New designs have to hold down both DDT&E and operating costs as well as be capable of flying many times (to take advantage of learning curves) and placing large amounts of mass in orbit (assuming the payloads are available and affordable). Cost is not the only relevant factor and unique mission requirements or the need for backup systems can favor creating a new vehicle line.



SOURCE: Martin-Marrietta.

Fig. B.7—Shuttle-C sidemount reference concept

Table B.8

COST SPREADSHEET FOR SHUTTLE-C

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Shuttle-C Life Cycle Costs		1988$		Discount rate=	5.00%														
2	Payload to 100 nm, 28.5		120000 lbs																	
3				1	2	3	4	5	6		8	9	10	11	12	13	14	15	16	
4	Fiscal Year			1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
5	Total DDT&E (TFU)		1224	30	151	308	410	261	64											
6	TFU (Non recurring)		656																	
7	TFU (Recurring)		568																	
8	Operations Costs (per flight)		120																	
9	Flights/year								1	3	3	3	3	3	3	3	3	3	2	
10	Cummulative Flights								1	4	7	10	13	16	19	22	25	28	30	
11	Production Build time 4 yrs																			
12	Ogive 20/30/30/20																			
13	Learning Curve		90%																	
14	Prod No	Vehicle Unit Cost																		
15	1	568.00				113.60	170.40	170.40	113.60											
16	2	511.20					102.24	153.36	153.36	102.24										
17	3	480.65					96.13	144.19	144.19	96.13										
18	4	460.08					92.02	138.02	138.02	92.02										
19	5	444.74						88.95	133.42	133.42	88.95									
20	6	432.58						86.52	129.77	129.77	86.52									
21	7	422.56						84.51	126.77	126.77	84.51									
22	8	414.07							82.81	124.22	124.22	82.81								
23	9	406.72							81.34	122.02	122.02	81.34								
24	10	400.26							80.05	120.08	120.08	80.05								
25	11	394.51								78.90	118.35	118.35	78.90							
26	12	389.32								77.86	116.80	116.80	77.86							
27	13	384.61								76.92	115.38	115.38	76.92							
28	14	380.31									76.06	114.09	114.09	76.06						
29	15	376.34									75.27	112.90	112.90	75.27						
30	16	372.66									74.53	111.80	111.80	74.53						
31	17	369.25										73.85	110.77	110.77	73.85					
32	18	366.05										73.21	109.82	109.82	73.21					
33	19	363.06										72.61	108.92	108.92	72.61					
34	20	360.24											72.05	108.07	108.07	72.05				
35	21	357.57											71.51	107.27	107.27	71.51				
36	22	355.06											71.01	106.52	106.52	71.01				
37	23	352.66												70.53	105.80	105.80	70.53			
38	24	350.39												70.08	105.12	105.12	70.08			
39	25	348.22												69.64	104.47	104.47	69.64			
40	26	346.15													69.23	103.85	103.85	69.23		
41	27	344.17													68.83	103.25	103.25	68.83		
42	28	342.28													68.46	102.68	102.68	68.46		
43	29	340.45														68.09	102.14	102.14	68.09	
44	30	338.70														67.74	101.61	101.61	67.74	
45	Total Production Cost =		11772.8755 (including TFU)																	
46	Annual Production Cost =			0	0	113.60	460.79	865.95	1183.35	1280.36	202.69	1153.21	1116.56	1087.48	1063.43	975.57	723.78	410.27	135.83	
47																				
48	Annual Ops Cost =			0	0	0.00	0.00	0.00	120.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	240.00	
49	Facilities Cost =																			
50																				
51	Total Ann Costs =			30.00	151.00	308.00	700.39	956.55	1253.75	1640.36	1562.69	1513.21	1476.56	1447.48	1423.43	1335.57	1083.78	770.27	375.83	
52	Cum LC Costs =			30.00	181.00	489.00	1189.39	2145.94	3399.69	5040.05	6602.74	8115.94	9592.50	11039.99	12463.42	13798.99	14882.78	15653.04	16028.88	
53																				
54	Insurance Costs =																			
55																				
56	Disc Total Ann Costs =			28.57	136.96	266.06	576.21	749.48	935.57	1165.77	1057.69	975.43	906.48	846.31	792.62	708.28	547.38	370.51	172.17	
57	Disc Cum LC Costs =			28.57	165.53	431.59	1007.80	1757.29	2692.86	3858.63	4916.32	5891.74	6798.22	7644.54	8437.16	9145.44	9692.83	10063.34	10235.51	
58																				
59	Total Ann Pounds to Leo =			0.00	0.00	0.00	0.00	0.00	120000.00	360000.00	360000.00	360000.00	360000.00	360000.00	360000.00	360000.00	360000.00	360000.00	240000.00	
60	Total Cum Pounds to Leo =			0.00	0.00	0.00	0.00	0.00	120000.00	480000.00	840000.00	1200000.00	1560000.00	1920000.00	2280000.00	2640000.00	3000000.00	3360000.00	3600000.00	
61																				
62	Dollars/Lb (LCC average) =								28330.76	10500.10	7860.40	6763.29	6149.04	5749.99	5466.41	5226.89	4960.93	4658.64	4452.47	
63	Dollars/Lb (Disc LCC average) =								22440.48	8038.81	5852.76	4909.79	4357.84	3981.53	3700.51	3464.18	3230.94	2995.04	2843.20	
64																				
65	Ann Costs Less DDT&E (TFU) =			0.00	0.00	0.00	290.39	695.55	1189.75	1640.36	1562.69	1513.21	1476.56	1447.48	1423.43	1335.57	1083.78	770.27	375.83	
66	Cum Costs Less DDT&E (TFU) =			0.00	0.00	0.00	290.39	985.94	2175.69	3816.05	5378.74	6891.94	8368.50	9815.99	11239.42	12574.99	13658.78	14429.04	14804.88	
67	Dollars/lb (average less DDT&E) =								18130.76	7950.10	6403.26	5743.29	5364.43	5112.49	4929.57	4763.25	4552.93	4294.36	4112.47	

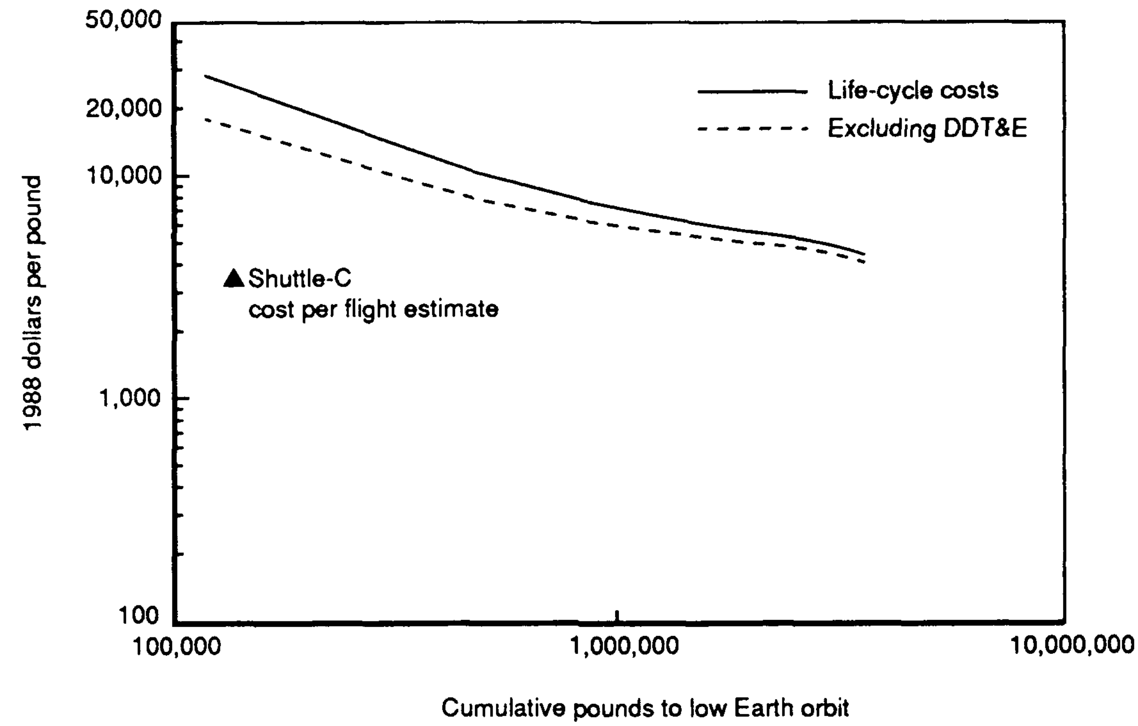


Fig. B.8—Launch costs for Shuttle-C

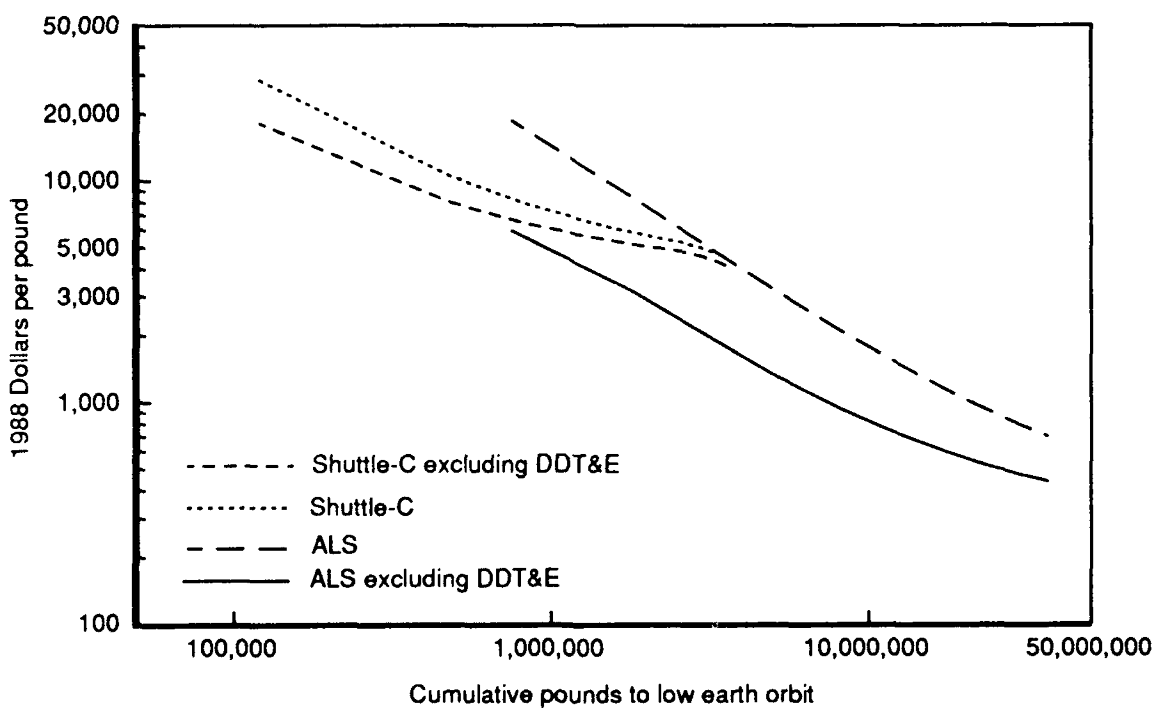


Fig. B.9—Launch costs for Shuttle-C and ALS (OTA)

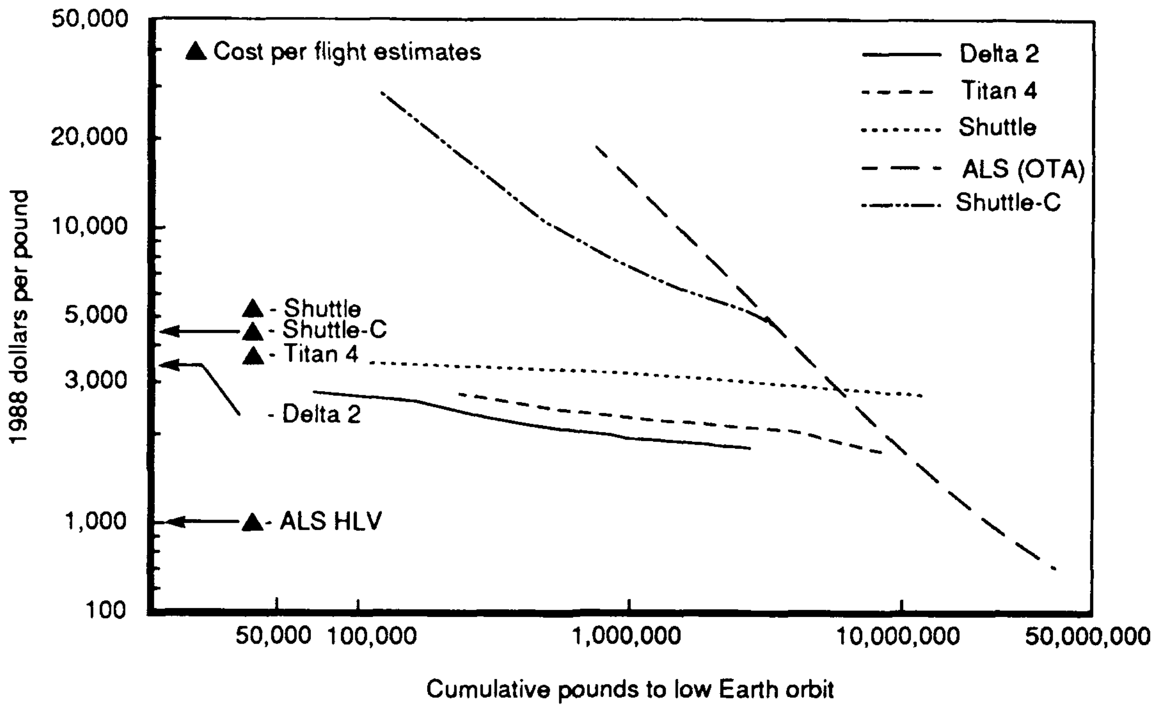


Fig. B.10—Launch costs for Delta, Titan, Shuttle, ALS, and Shuttle-C

In summary, the following observations are drawn, based on the material shown here:

- The Shuttle-C does not appear to be a competitive concept on cost grounds with other means of placing payloads in LEO.
- The ALS heavy-lift vehicle appears desirable if a case can be made for placing large amounts of mass into LEO. Costs of $1000 per pound appear achievable, but getting below that level will be increasingly difficult. Reaching that level will require deploying a cumulative mass significantly above past experiences.
- The shuttle is more expensive than current ELVs, but may be competitive based on unique needs of its payloads. An unknown portion of the shuttle's cost results from its having a crew and thus being man-rated.
- The Titan 4 and Delta 2 are the least expensive in terms of cost per pound, but they service very different payload sizes and thus are unlikely to be directly competitive.

Appendix C
U.S. GOVERNMENT SPENDING ON SPACE

The purpose of this appendix is to provide an overview of U.S. government spending for space activities. The likely budget ranges for future space activities are required before selecting fiscally feasible space transportation options. Such feasibility can depend not only on the amount of gross national product (GNP) required, but also on the percentage of total government outlays affected. The latter point can be a proxy estimate for political feasibility as well.

C.1 HISTORICAL DATA

The historical record of U.S. government (USG) spending on space was reviewed as well as economic data from various official sources.[1] A spreadsheet was created with data from fiscal years 1961–1988 and projections for 1989–2010 (see Table C.1). The columns contain data for:

- Gross national product in current and 1988 dollars;
- All DoD-military outlays (OMB function 051),[2] excluding nuclear energy defense and related activities in current and 1988 dollars;
- U.S. Air Force outlays in current and 1988 dollars;
- NASA outlays minus those for air transportation (OMB subfunction 402) in current and 1988 dollars;
- DoD space-related outlays in current and 1988 dollars;
- All other U.S. government space-related outlays in current and 1988 dollars for the Departments of Energy, Commerce, Interior, and Agriculture, and the National Science Foundation (estimates of up to $3 million were added in 1987 and beyond for Department of Transportation regulatory activities);
- Annual totals of all space-related government outlays in 1988 dollars; and
- Total government outlays in current and 1988 dollars.

C.2 PROJECTED DATA

The spreadsheet (Table C.2) was set up to handle a variety of growth projections. As a baseline case, the following average growth rates were assumed:

[1]See Office of Management and Budget, *Historical Tables, Budget of the United States Government, Fiscal Year 1989*, U.S. Government Printing Office, Washington, D.C., 1988; Office of Management and Budget, *Budget of the United States Government, Fiscal Year 1989*, U.S. Government Printing Office, Washington, D.C., 1988; U.S. Air Force, *The United States Air Force Summary, Fiscal Years 1988/89*, Deputy Comptroller of the Air Force for Cost and Economics, Economics and Field Support Division, Washington, D.C., 1987; Office of Science and Technology Policy, *Aeronautics and Space Report of the President 1986*, Executive Office of the President, U.S. Government Printing Office, Washington, D.C., 1987; and Aerospace Industries Association, Aerospace Facts and Figures 1987–88, McGraw-Hill, Washington, D.C., 1987.

[2]The federal budget follows a structure of grouping activities by functions, subfunctions, and programs. Federal spending is classified in the functional structure according to the primary purpose of the activity, disregarding agency and organizational distinctions to the extent feasible. See *Budget of the United States Government, Fiscal Year 1989*, op. cit., p. 5–2.

- GNP grows at a real rate of 2.4 percent per year;
- Total government outlays are assumed to grow at same rate as GNP;
- 0 percent real growth in DoD (051) outlays above $285.5 billion in 1989;
- 2 percent real growth in NASA (less air transportation) above $10.2 billion in 1989;
- 2 percent real growth in DoD space outlays above $17 billion in 1989; and
- 0 percent real growth all other USG space outlays above $380 million in 1989.

C.3 DATA DISPLAYS

To bring out trends in the data more clearly, several different graphs were made. Figure C.1 shows USG outlays in 1988 dollars for space-related activities of NASA, the DoD, and other agencies. The time period is 1961–1988. In 1983, DoD space spending surpassed that of NASA.

Figure C.2 shows the same data as Fig. C.1, but as a percentage of all USG outlays in 1988 dollars. The increase in total space spending in recent years is driven by increased DoD spending. In 1988, total space spending was 2.25 percent of all USG outlays.

Figure C.3 shows the same data as Fig. C.1, but as a percentage of GNP. NASA spending has been essentially flat since the end of the Apollo program in the early 1970s. In 1988, total space spending was 0.5 percent of GNP.

Figure C.4 shows the historical percentage of military-related space spending to all DoD (function 051) outlays. By 1988, this had climbed to 5.4 percent. The second curve shows the ratio, in 1988 dollars, of DoD to NASA space spending. Having usually stayed under 1.0 in the past, DoD space spending now exceeds NASA spending by 60 to 100 percent.

C.4 SPACE AND OTHER DOD EXPENSES

As space appears to be of increasing importance to the Department of Defense on a budgetary basis alone, a comparison was made with other DoD expenses. A bar chart was made of actual 1987 DoD outlays (function 051) by mission category. See Fig. C.5 below and the Table C.2 data sheet.[3]

DoD spending for space activities overlaps many areas, such as research and development, strategic forces, and general purpose forces, so direct comparisons are misleading. Nonetheless, if DoD space was called out as a separate mission category, its $15 billion budget would be about what the DoD spends on its Guard and Reserve forces. At a 2 percent real growth rate, space would approach current expenditure levels for strategic forces by the year 2000.

Spending within the Strategic Defense Initiative Organization (SDIO) partially overlaps DoD space spending.[4] Some program elements within SDIO such as the Boost Surveillance and Tracking System (BSTS) and the Space Surveillance and Tracking System (SSTS) are included in DoD space spending figures. If SDIO funding were eliminated, it is likely that these programs would be continued by the Air Force as part of its surveillance activities. It is thus sufficient to look at DoD space spending figures alone without adding SDIO spending. Figure C.6 provides some perspective for the relative sizes of SDIO and DoD space spending, keeping in mind the problem of overlap.

SDIO spending is about one quarter of total DoD space spending. Recent cost estimates for a Phase I strategic defense architecture, based on a constellation of space-based intercep-

[3] *Budget of the United States Government, Fiscal Year 1989*, op. cit., p. 5–8.

[4] Letter from Dennis Granato, Deputy for Space and Advanced Systems, Office of the Director of Defense Research and Engineering, to the author, 23 November 1988.

Table C.1

FEDERAL SPACE ACTIVITIES SPREADSHEET

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2	Federal Space Activities			Millions$		Outlays	1961-1988		See also Aeronautics and Space Report								(Interior, Agri
3				Current and 1988 dollars (GNP deflator)					No Function 402		Space		Other		Space	Space	Space
4	Reference	USAF p A-3	USAF p A-11		USAF p A-18	Function 051	USAF p A-22		AIA 87-88		AIA 87-88		Space=	Other	AIA 87-88	AIA 87-88	AIA 87-88
5	Year	GNP	Deflator	GNP(88$)	All DoD	All DoD(88$)	USAF	USAF(88$)	NASA	NASA(88$)	DoD	DoD(88$)	E+C+O	Space (88$)	Energy	Commerce	Other
6	1961	519000	0.244	2127049.18	43.3	177.46	19.8	81.15	693.6	2842.62	710	2909.84	64.3	263.52	64.3	0	0
7	1962	556600	0.244	2281147.54	46.8	191.80	20.8	85.25	1225.9	5024.18	1028.8	4216.39	131.9	540.57	130	1	0.9
8	1963	588600	0.244	2412295.08	47.9	196.31	20.6	84.43	2516.8	10314.75	1367.5	5604.51	194.3	796.31	181	12.2	1.1
9	1964	629400	0.244	2579508.20	49.5	202.87	20.5	84.02	4131.3	16931.56	1563.5	6407.79	235	963.11	220.1	12.3	2.6
10	1965	673600	0.248	2716129.03	45.9	185.08	18.1	72.98	5035	20302.42	1591.8	6418.55	259.3	1045.56	232.2	24.1	3
11	1966	740500	0.256	2892578.13	54.1	211.33	20.1	78.52	5857.9	22882.42	1637.4	6396.09	223.2	871.88	188.3	28.1	6.8
12	1967	793500	0.258	3075581.40	67.4	261.24	22.9	88.76	5336.7	20684.88	1673.1	6484.88	227.5	881.78	183.6	38.6	5.3
13	1968	852400	0.263	3241064.64	77.3	293.92	25.7	97.72	4595.3	17472.62	1890.2	7187.07	181.2	688.97	146.5	29	5.7
14	1969	929500	0.273	3404761.90	77.8	284.98	25.9	94.87	4078	14937.73	2095	7673.99	153.1	560.81	117.5	31	4.6
15	1970	990500	0.283	3500000.00	77.1	272.44	24.9	87.99	3565.2	12597.88	1756.1	6205.30	131.9	466.08	102.6	24	5.3
16	1971	1057100	0.294	3595578.23	74.5	253.40	23.8	80.95	3171	10785.71	1693	5758.50	135	459.18	97.3	29.8	7.9
17	1972	1151200	0.307	3749837.13	75.1	244.63	24	78.18	3194.9	10406.84	1470	4788.27	106.9	348.21	59.6	37.4	9.9
18	1973	1285500	0.345	3726086.96	73.2	212.17	23.6	68.41	3069.4	8896.81	1557	4513.04	93	269.57	51.1	29.4	12.5
19	1974	1417000	0.419	3381861.58	77.6	185.20	23.9	57.04	2960.4	7065.39	1777	4241.05	116.5	278.04	38.8	64	13.7
20	1975	1523500	0.473	3220930.23	84.9	179.49	25	52.85	2950.9	6238.69	1831.1	3871.25	108.8	230.02	34.3	63.6	10.9
21	1976	1699600	0.502	3385657.37	87.9	175.10	26.4	52.59	3336.3	6646.02	1864.4	3713.94	113.2	225.50	25.7	71.1	18.4
22	1977	1935800	0.533	3631894.93	95.6	179.36	27.9	52.35	3599.5	6753.28	1832.7	3438.46	126.9	238.09	22.2	86.9	17.8
23	1978	2173400	0.576	3773263.89	103	178.82	29.2	50.69	3582.4	6219.44	2457	4265.63	148.8	258.33	28.6	100.7	19.5
24	1979	2452200	0.651	3766820.28	115	176.65	32.3	49.62	3743.9	5751.00	2891.8	4442.09	172.6	265.13	54.7	97.4	20.5
25	1980	2667600	0.755	3533245.03	132.8	175.89	39	51.66	4340.1	5748.46	3162.3	4188.48	165.3	218.94	48.8	88.7	27.8
26	1981	2986200	0.841	3550772.89	156.1	185.61	46.7	55.53	4877.1	5799.17	4130.5	4911.41	157.9	187.75	46.9	81	30
27	1982	3141500	0.872	3602637.61	182.9	209.75	55.1	63.19	5463.3	6265.25	4771.5	5471.90	231.4	265.37	59.5	142.4	29.5
28	1983	3320900	0.885	3752429.38	205	231.64	62.9	71.07	6100.9	6893.67	6246.7	7058.42	242.8	274.35	39.6	178	25.2
29	1984	3695300	0.904	4087721.24	220.8	244.25	68.6	75.88	6461.4	7147.57	8000.2	8849.78	264.5	292.59	33.4	208.7	22.4
30	1985	3936800	0.907	4340463.07	245.4	270.56	82	90.41	6607.4	7284.90	10441.3	11511.91	207.1	228.34	34	155.4	17.7
31	1986	4163300	0.933	4462272.24	265.6	284.67	91.2	97.75	6755.7	7240.84	11850.4	12701.39	560.4	600.64	36.4	505.3	18.7
32	1987	4424300	0.965	4584766.84	274	283.94	92.8	96.17	6956.5	7208.81	13973.4	14480.21	337.6	349.84	39.1	278.2	20.3
33	1988	4735300	1	4735300.00	277.3	277.30	94	94.00	8434.7	8434.70	15000	15000.00	364	364.00	40	300	24
34																	
35	Projections	2.40%	average real growth		0%	real growth				0.00%	real growth	6.50%	real growth	0%	real growth		
36	Year			GNP(88$)		All DoD(88$)		USAF(88$)		NASA(88$)		DoD(88$)		E+C+O	Energy	Commerce	Other
37	1989			4848947.20		285.50		95.30		10180.8		17000		380			
38	1990			4965321.93		285.50		95.30		10180.80		18105.00		380			
39	1991			5084489.66		285.50		95.30		10180.80		19281.83		380			
40	1992			5206517.41		285.50		95.30		10180.80		20535.14		380			
41	1993			5331473.83		285.50		95.30		10180.80		21869.93		380			
42	1994			5459429.20		285.50		95.30		10180.80		23291.47		380			
43	1995			5590455.50		285.50		95.30		10180.80		24805.42		380			
44	1996			5724626.43		285.50		95.30		10180.80		26417.77		380			
45	1997			5862017.47		285.50		95.30		10180.80		28134.93		380			
46	1998			6002705.89		285.50		95.30		10180.80		29963.70		380			
47	1999			6146770.83		285.50		95.30		10180.80		31911.34		380			
48	2000			6294293.33		285.50		95.30		10180.80		33985.57		380			
49	2001			6445356.37		285.50		95.30		10180.80		36194.64		380			
50	2002			6600044.92		285.50		95.30		10180.80		38547.29		380			
51	2003			6758446.00		285.50		95.30		10180.80		41052.86		380			
52	2004			6920648.70		285.50		95.30		10180.80		43721.30		380			
53	2005			7086744.27		285.50		95.30		10180.80		46563.18		380			
54	2006			7256828.13		285.50		95.30		10180.80		49589.79		380			
55	2007			7430989.96		285.50		95.30		10180.80		52813.12		380			
56	2008			7609333.72		285.50		95.30		10180.80		56245.98		380			
57	2009			7791957.73		285.50		95.30		10180.80		59901.97		380			
58	2010			7978964.72		285.50		95.30		10180.80		63795.59		380			

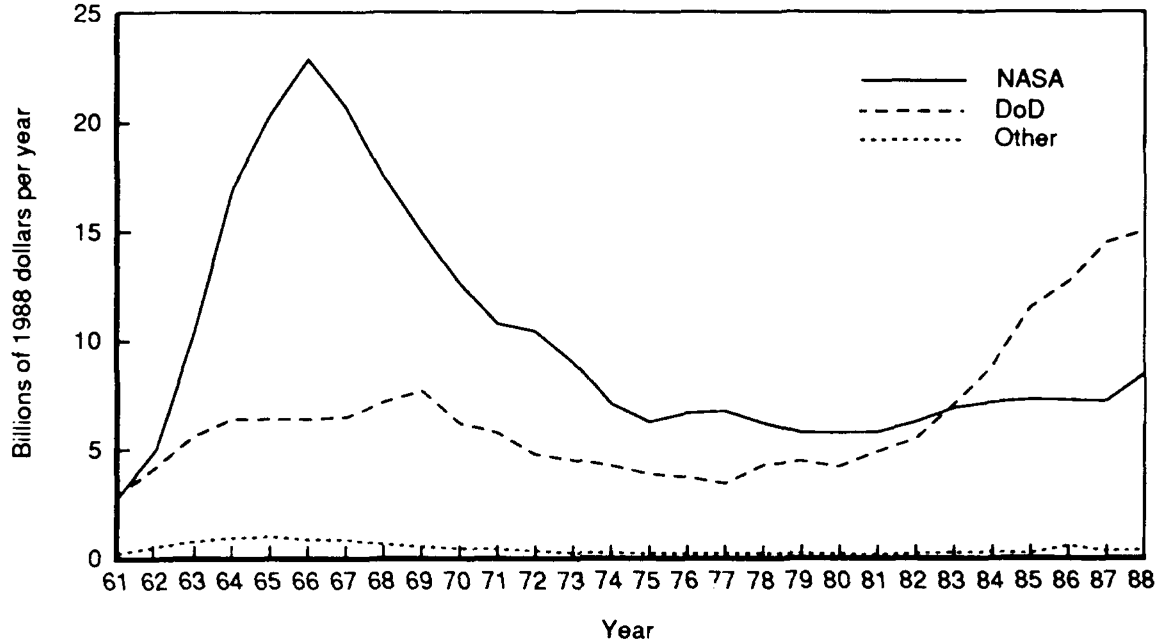
Table C.1—(continued)

	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
1																	
2	ulture, NSF,	Transportation?,															
3				USAF p A-9													
4			88$	Current$B	88$			DoD	DoD		Outlays	Outlays	Outlays				
5		Year	All Space $	USG Outlays	USG Outlays	Space/GNP%	NASA/GNP%	Space/GNP%	Space/DoD%	DoD/NASA	Space/USG	DoDSpace/USG	NASA/USG	AF/DoD%	NASA(88$)	DoD(88$)	Other Space (88$)
6		1961	6015.98	97.70	400.41	0.28	0.13	0.14	1.64	1.02	1.50	0.73	0.71	45.73	2842.62	2909.83607	263.52459
7		1962	9781.15	106.80	437.70	0.43	0.22	0.18	2.20	0.84	2.23	0.96	1.15	44.44	5024.18	4216.39344	540.57377
8		1963	16715.57	111.30	456.15	0.69	0.43	0.23	2.85	0.54	3.66	1.23	2.26	43.01	10314.75	5604.5082	798.311475
9		1964	24302.46	118.50	485.66	0.94	0.66	0.25	3.16	0.38	5.00	1.32	3.49	41.41	16931.56	6407.78689	963.114754
10		1965	27766.53	118.20	476.61	1.02	0.75	0.24	3.47	0.32	5.83	1.35	4.26	39.43	20302.42	6418.54839	1045.56452
11		1966	30150.39	134.50	525.39	1.04	0.79	0.22	3.03	0.28	5.74	1.22	4.36	37.15	22882.42	6396.09375	871.875
12		1967	28051.55	157.50	610.47	0.91	0.67	0.21	2.48	0.31	4.60	1.06	3.39	33.98	20684.88	6484.88372	881.782946
13		1968	25348.67	178.10	677.19	0.78	0.54	0.22	2.45	0.41	3.74	1.06	2.58	33.25	17472.62	7187.07224	688.973384
14		1969	23172.53	183.60	672.53	0.68	0.44	0.23	2.69	0.51	3.45	1.14	2.22	33.29	14937.73	7673.99267	560.805861
15		1970	19269.26	195.60	691.17	0.55	0.36	0.18	2.28	0.49	2.79	0.90	1.82	32.30	12597.88	6205.30035	486.077739
16		1971	17003.40	210.20	714.97	0.47	0.30	0.16	2.27	0.53	2.38	0.81	1.51	31.95	10785.71	5758.5034	459.183673
17		1972	15543.32	230.70	751.47	0.41	0.28	0.13	1.96	0.46	2.07	0.64	1.38	31.96	10406.84	4788.27362	348.208469
18		1973	13679.42	245.70	712.17	0.37	0.24	0.12	2.13	0.51	1.92	0.63	1.25	32.24	8896.81	4513.04348	269.565217
19		1974	11584.49	269.40	642.96	0.34	0.21	0.13	2.29	0.60	1.80	0.66	1.10	30.80	7065.39	4241.05012	278.042959
20		1975	10339.96	332.30	702.54	0.32	0.19	0.12	2.16	0.62	1.47	0.55	0.89	29.45	6238.69	3871.24736	230.021142
21		1976	10585.46	371.80	740.64	0.31	0.20	0.11	2.12	0.56	1.43	0.50	0.90	30.03	6646.02	3713.94422	225.498008
22		1977	10429.83	409.20	767.73	0.29	0.19	0.09	1.92	0.51	1.36	0.45	0.88	29.18	6753.28	3438.48154	238.086304
23		1978	10743.40	458.70	796.35	0.28	0.16	0.11	2.39	0.69	1.35	0.54	0.78	28.35	6219.44	4265.625	258.333333
24		1979	10458.22	503.50	773.43	0.28	0.15	0.12	2.51	0.77	1.35	0.57	0.74	28.09	5751.00	4442.08909	265.130568
25		1980	10155.89	590.90	782.65	0.29	0.16	0.12	2.38	0.73	1.30	0.54	0.73	29.37	5748.48	4188.47682	218.940397
26		1981	10898.34	678.20	806.42	0.31	0.16	0.14	2.65	0.85	1.35	0.61	0.72	29.92	5799.17	4911.41498	187.752675
27		1982	12002.52	745.70	855.16	0.33	0.17	0.15	2.61	0.87	1.40	0.64	0.73	30.13	6265.25	5471.90367	265.366972
28		1983	14226.44	808.30	913.33	0.38	0.18	0.19	3.05	1.02	1.56	0.77	0.75	30.68	6893.67	7058.41808	274.350282
29		1984	16289.93	851.80	942.26	0.40	0.17	0.22	3.62	1.24	1.73	0.94	0.76	31.07	7147.57	8849.77876	292.588496
30		1985	19025.14	946.30	1043.33	0.44	0.17	0.27	4.25	1.58	1.82	1.10	0.70	33.41	7284.90	11511.9074	228.335171
31		1986	20542.87	990.30	1061.41	0.46	0.16	0.28	4.48	1.75	1.94	1.20	0.68	34.34	7240.84	12701.3934	600.643087
32		19[illegible]	22038.86	1004.60	1041.04	0.48	0.16	0.32	5.10	2.01	2.12	1.39	0.69	33.87	7208.81	14480.2073	349.84456
33		1988	23798.70	1055.90	1055.90	0.50	0.18	0.32	5.41	1.78	2.25	1.42	0.80	33.90	8434.70	15000	364
34																	
35		Projections			Growth =				DoD	DoD	Outlays	Outlays	Outlays				
36		Year	All Space $		2.40%	Year	Space/GNP%	NASA/GNP%	Space/GNP%	Space/DoD%	DoD/NASA	Space/USG	DoDSpace/USG	NASA/USG	AF/DoD%	NASA(88$)	DoD(88$)
37		89	27560.80	USG Outlays=	1094.20	89	0.57	0.21	0.35	5.95	1.67	2.52	1.55	0.93	33.38	10180.80	17000
38		90	28665.80		1100.00	90	0.58	0.21	0.36	6.34	1.78	2.61	1.65	0.93	33.38	10180.80	18105
39		91	29842.63		1126.40	91	0.59	0.20	0.38	6.75	1.89	2.65	1.71	0.90	33.38	10180.80	19281.825
40		92	31095.94		1153.43	92	0.60	0.20	0.39	7.19	2.02	2.70	1.78	0.88	33.38	10180.80	20535.1436
41		93	32430.73		1181.12	93	0.61	0.19	0.41	7.66	2.15	2.75	1.85	0.86	33.38	10180.80	21869.928
42		94	33852.27		1209.46	94	0.62	0.19	0.43	8.16	2.29	2.80	1.93	0.84	33.38	10180.80	23291.4733
43		95	35366.22		1238.49	95	0.63	0.18	0.44	8.69	2.44	2.86	2.00	0.82	33.38	10180.80	24805.419
44		96	36978.57		1268.21	96	0.65	0.18	0.46	9.25	2.59	2.92	2.08	0.80	33.38	10180.80	26417.7713
45		97	38695.73		1298.65	97	0.66	0.17	0.48	9.85	2.76	2.98	2.17	0.78	33.38	10180.80	28134.9264
46		98	40524.50		1329.82	98	0.68	0.17	0.50	10.50	2.94	3.05	2.25	0.77	33.38	10180.80	29963.6966
47		99	42472.14		1361.73	99	0.69	0.17	0.52	11.18	3.13	3.12	2.34	0.75	33.38	10180.80	31911.3369
48		0	44546.37		1394.42	0	0.71	0.16	0.54	11.90	3.34	3.19	2.44	0.73	33.38	10180.80	33985.5738
49		1	46755.44		1427.88	1	0.73	0.16	0.56	12.68	3.56	3.27	2.53	0.71	33.38	10180.80	36194.6361
50		2	49108.09		1462.15	2	0.74	0.15	0.58	13.50	3.79	3.36	2.64	0.70	33.38	10180.80	38547.2875
51		3	51613.66		1497.24	3	0.76	0.15	0.61	14.38	4.03	3.45	2.74	0.68	33.38	10180.80	41052.8611
52		4	54282.10		1533.18	4	0.78	0.15	0.63	15.31	4.29	3.54	2.85	0.66	33.38	10180.80	43721.2971
53		5	57123.98		1569.97	5	0.81	0.14	0.66	16.31	4.57	3.64	2.97	0.65	33.38	10180.80	46563.1814
54		6	60150.59		1607.65	6	0.83	0.14	0.68	17.37	4.87	3.74	3.08	0.63	33.38	10180.80	49589.7882
55		7	63373.92		1646.24	7	0.85	0.14	0.71	18.50	5.19	3.85	3.21	0.62	33.38	10180.80	52813.1245
56		8	66806.78		1685.75	8	0.88	0.13	0.74	19.70	5.52	3.96	3.34	0.60	33.38	10180.80	56245.9775
57		9	70462.77		1726.20	9	0.90	0.13	0.77	20.98	5.88	4.08	3.47	0.59	33.38	10180.80	59901.9661
58		10	74356.39		1767.63	10	0.93	0.13	0.80	22.35	6.27	4.21	3.61	0.58	33.38	10180.80	63795.5939

Table C.2

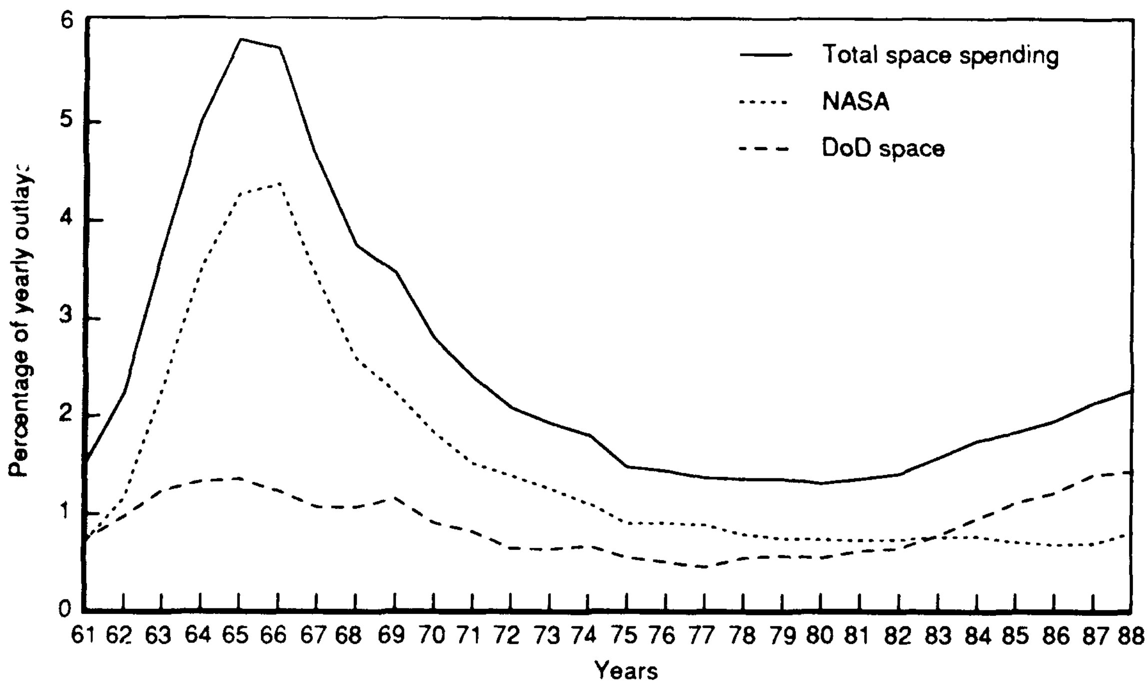
MISSION CATEGORIES FOR MILITARY DEFENSE

	A	B	C	D	E	F	G
1							
2		Mission Categories for Defense, Military					
3		Function Code 051		$Billions			
4							
5		Major Mission		1987 Actual	1988 Est.	1989 Est	
6		Strategic forces		21.1	21	23.4	
7		General purpose forces		114.9	110.7	114.1	
8		Intell & Comm.		27.7	28	28.1	
9		Air & Sealift		7.1	5.6	5.9	
10		Guard & Reserve		15.7	16.2	16.6	
11		R&D		27.5	32.5	32.6	
12		Supply & Maint.		22.7	24.1	24.1	
13		General personnel		35.5	35.9	36.6	
14		Administration		6.6	5.8	6	
15		Other nations		0.7	0.8	0.8	
16		Special Ops		0	2.6	2.6	
17		Total Budget Authority		279.5	283.2	290.8	
18							
19		Appropriated Budget Authority - then-year $M					
20			FY85	FY86	FY87	FY88	FY89
21		DoD Space	10441.3	11850.4	13973.4	15000	17000
22		SDIO	1500	2750	3500	3900	4080
23		SDI%	14.37	23.21	25.05	26.00	24.00



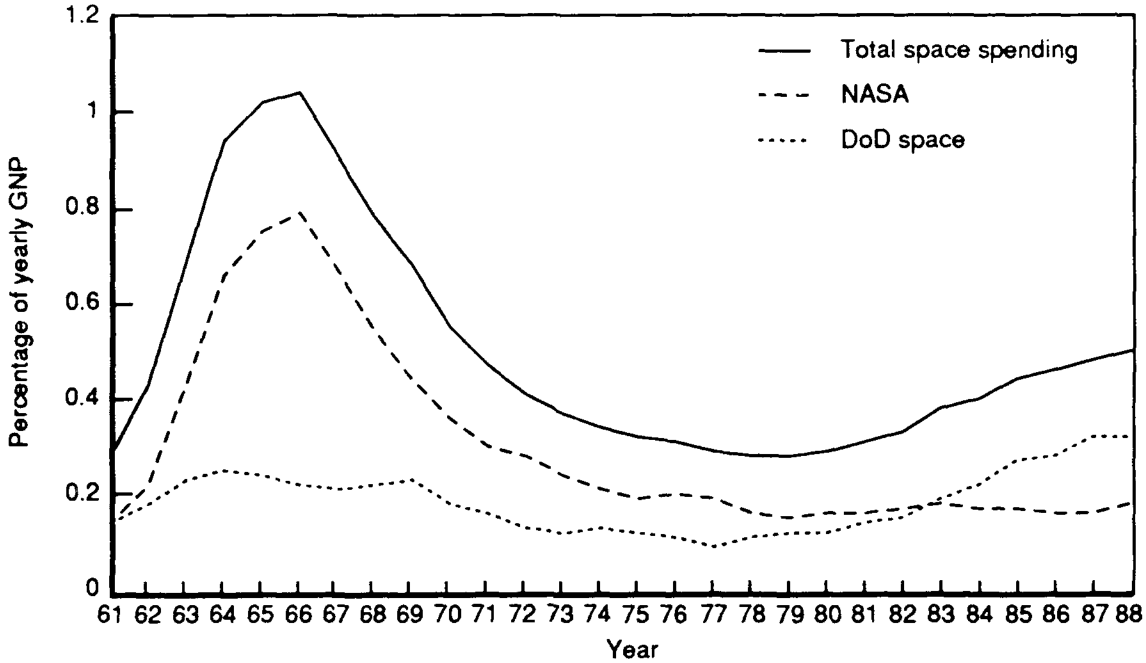
SOURCE: Office of Management and Budget

Fig. C.1—U.S. government space spending



SOURCE: Office of Management and Budget

Fig. C.2—Space as a percent of U.S. government outlays



SOURCE: Office of Management and Budget

Fig. C.3—Space as a percent of GNP

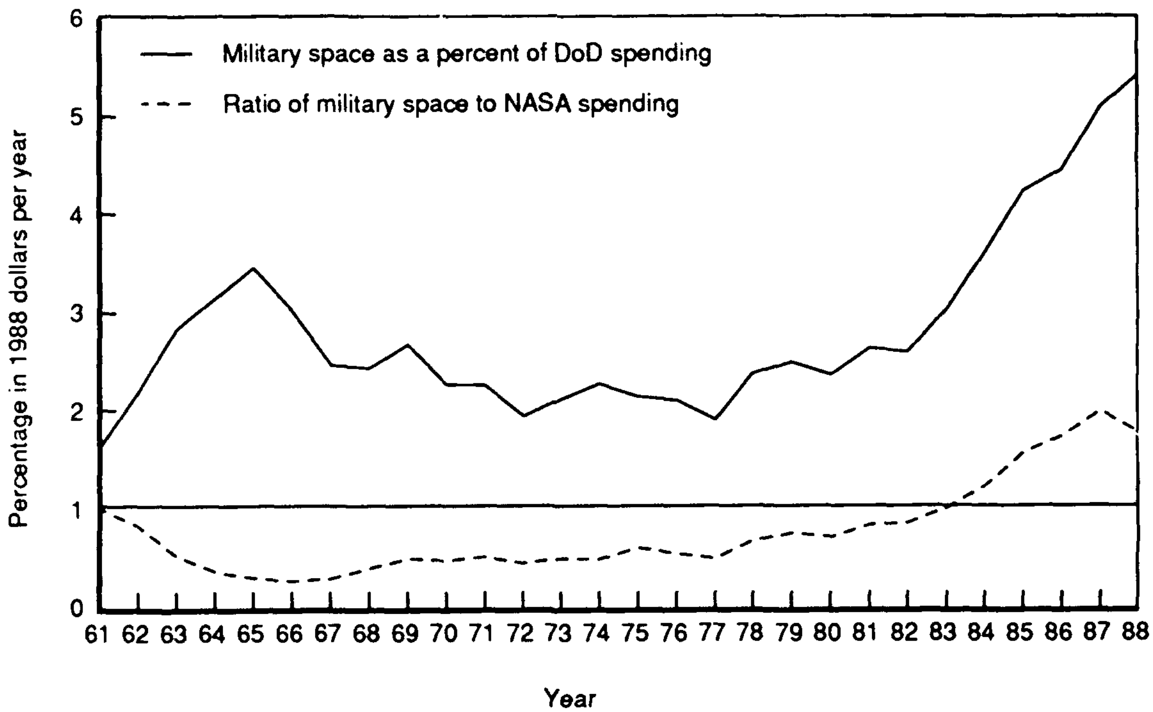
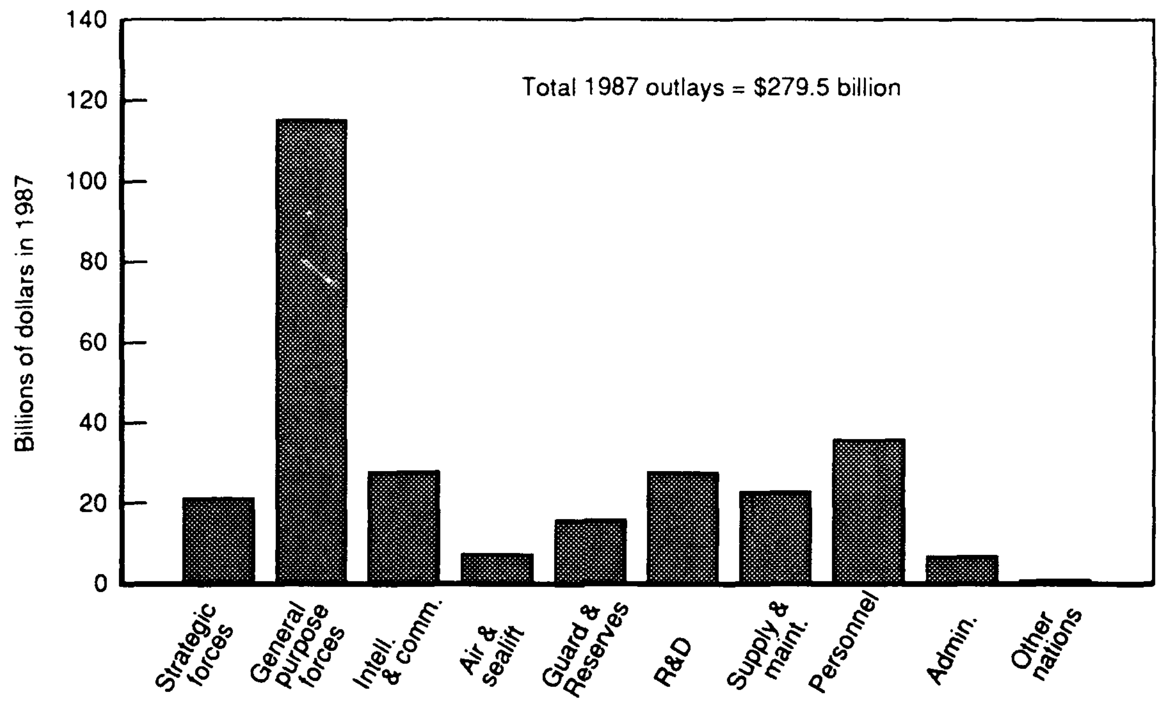


Fig. C.4—DoD space spending



SOURCE: Office of Management and Budget.

Fig. C.5—Major missions in defense budget area 051

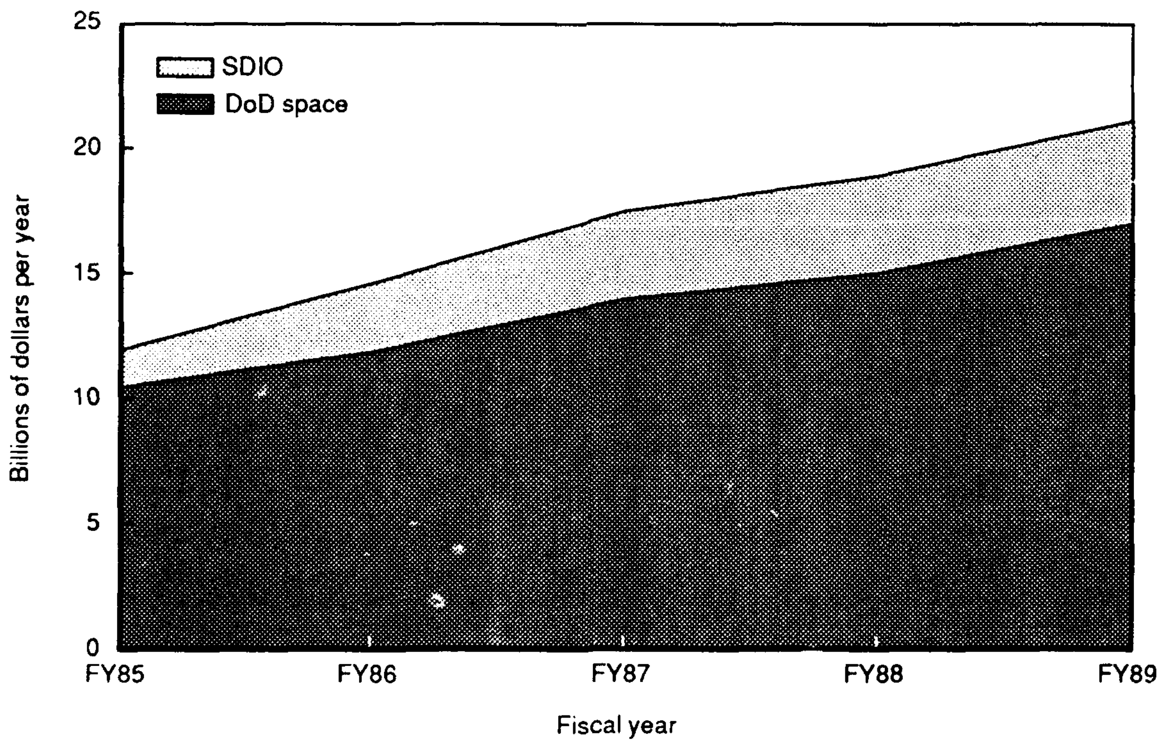


Fig. C.6—Appropriated DoD budget authority

tors, come to about $70 billion.[5] Even if spread over a decade, this would mean SDIO spending would rise to about 40 to 50 percent of DoD space spending for a Phase I deployment.

The Office of Management and Budget calls out subfunction 253 for civil space flight (within function 250, General Science, Space, and Technology). For 1987, outlays for subfunction 253 were $4.1 billion, and were estimated to grow in 1988 to $5.2 billion in current dollars.[6] In a briefing before the National Space Club in June 1987, Maj. Gen. Robert Rankine said that the Air Force will spend about $3–4 billion in 1988 for launch services, R&D, and ground-related support of military space activities.[7] Taking these figures at face value would mean that the United States currently spends about $8 billion yearly on access to space, or about $1 billion more than the DoD alone spends on airlift and sealift.

C.5 POTENTIAL OUTLAYS FOR EXPANDED CIVIL SPACE EFFORTS

In recent years there have been several reports and studies on expanding the level of civil space activities to include manned return to the Moon and missions to Mars.[8] In 1988, the staff of the Senate Commerce subcommittee on Science, Technology and Space examined the implied NASA budget estimates from these reports, and made estimates of their own, to compare the possible sizes of the NASA budget out to fiscal year 2000.[9]

Figure C.7 and the related data in Table C.3 show the summary of potential civil space budgets made by the Senate Appropriations subcommittee staff. The Congressional Budget Office (CBO) set a baseline figure of about $9 billion in 1988 dollars for NASA, expecting it to be a continuation of current resources. However, given the expenses associated with the Challenger loss and the increased cost of shuttle flights at a lower flight rate, maintaining this baseline will mean actual decreases in the scope of NASA programs from prior years. The CBO core option projects required NASA budgets of up to $16 billion, in 1988 dollars, to maintain pre-accident plans for the space station, space science, and space transportation capacity (e.g., buying additional ELVs).

The National Commission on Space (NCOS) and American Institute of Aeronautics and Astronautics (AIAA) reports called for ambitious plans to develop new launch vehicles, an extensive "infrastructure" in near-Earth space of space platforms, space transfer vehicles in addition to the space station, and human outposts on the Moon and eventually Mars. Both reports called for steady, increasing NASA funding over the long term.

The Senate staffers examined three of the NASA/Ride Report options: an expanded program of Earth observation and environmental monitoring, an outpost on the Moon, and an outpost on Mars. These options were combined into two scenarios, one with both Earth observation and a lunar outpost, and one with Earth observation and a Martian outpost. The funding profile in these cases was much steeper and yet leveled out at about the same amount—a NASA budget of over $30 billion in 1988 dollars.

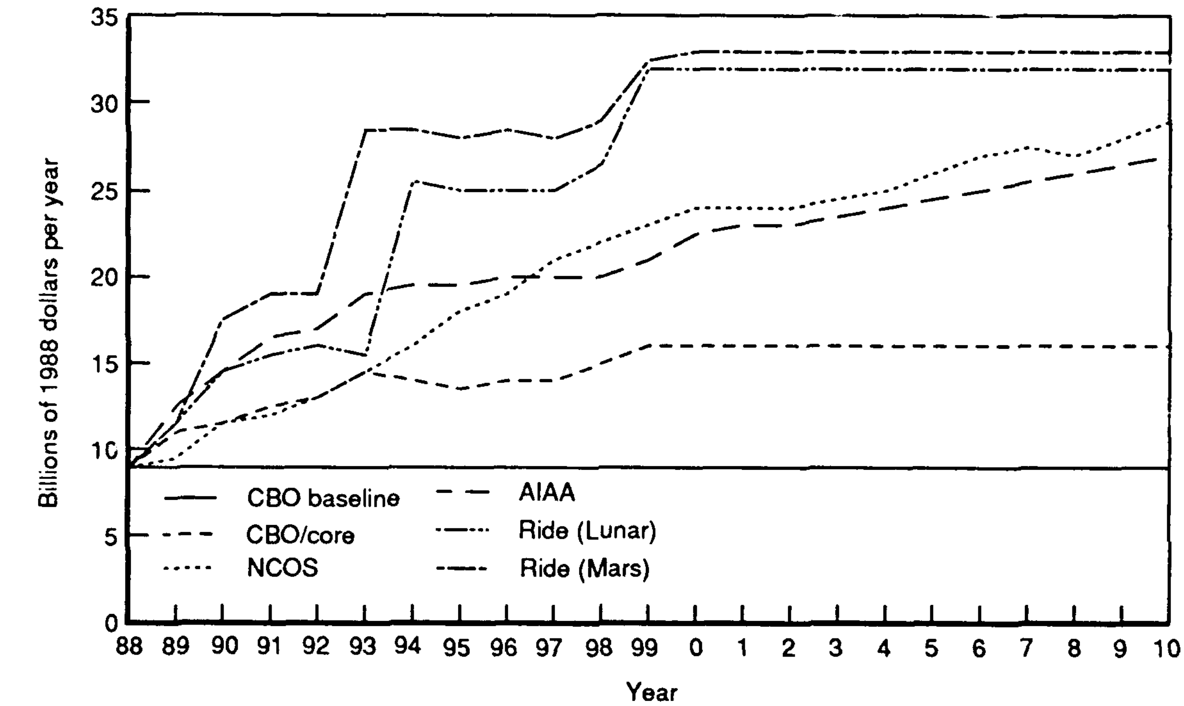
[5]Michael Mecham, "Cuts in Space-Based Interceptors Reduce Strategic Defense Costs," *Aviation Week & Space Technology*, October 10, 1988, p. 25.

[6]*Historical Tables*, op. cit., p. 56.

[7]Maj. Gen. Robert Rankine, USAF, *Progress in Space*, briefing to the National Space Club, Washington, D.C., June 27, 1987.

[8]See National Commission on Space, *Pioneering the Space Frontier*, Bantam Books, New York, 1986; Congressional Budget Office, *The 1988 Budget and the Future of the NASA Program*, Staff Working Paper, Washington, D.C., March 1987; Sally K. Ride, *Leadership and America's Future in Space*, NASA Headquarters, Washington, D.C., August 1987; and American Institute of Aeronautics & Astronautics, *The Civil Space Program: An Investment in America*, Washington, D.C., December 1987.

[9]"NASA Wins Policy Dispute Over Space Shuttle Pricing," *Aviation Week & Space Technology*, April 4, 1988, p. 20.



SOURCE: U.S. Senate

Fig. C.7—Potential civil space budgets

C.6 AFFORDABILITY OF EXPANDED CIVIL SPACE EFFORTS

Because the more ambitious projections require a tripling of NASA's budget over 12 years, the obvious question of affordability arises. The results of Fig. C.7 were converted into percentages of GNP, which grew at an annual real rate of 2.4 percent (see Fig. C.8). The assumption of positive GNP growth helps to flatten the curves and both the NCCS and AIAA estimates show an essentially flat rate of GNP consumption past the year 2000.

All current government space activities equal 0.5 percent of GNP. All current government outlays equal about 22 percent of GNP. (See Fig. C.9). At the height of the Apollo program (1965–1966), the United States spent about 1 percent of its GNP on space activities. The most ambitious plans for an expanded civil space effort would require about half that peak amount. If there was no real growth in GNP, the $32 billion peak expense for civil space would require about 0.67 percent of GNP in the year 2000. Of course, if DoD efforts continue to expand, then over 1 percent of GNP may be required for space activity, depending on the chosen military programs.

Measured another way, all space outlays account for 2.25 percent of total government outlays. NASA accounts for 0.8 percent of that amount. After subtracting payments to individuals, defense spending, and interest on the debt, all other government spending accounts for 10 percent of total government outlays. (See Fig. C.10). NASA budget increases

Table C.3

POTENTIAL CIVIL SPACE BUDGETS SPREADSHEET

	A	B	C	D	E	F	G	H
1								
2		Potential Civil Space Budgets			$88 Billions			
3		1988 -2010			Aeronautics is about 10% of CBO baseline & core			
4								
5					See Aviation Week, 4/4/88			
6	Years	CBO Baseline	CBO Core	NCOS	AIAA	Ride (Lunar)	Ride (Mars)	
7	1988	9	9	9	9	9	9	
8	1989	9	11	9.5	12.5	11.5	11.5	
9	1990	9	11.5	11.5	14.5	14.5	17.5	
10	1991	9	12.5	12	16.5	15.5	19	
11	1992	9	13	13	17	16	19	
12	1993	9	14.5	14.5	19	25.5	28.5	
13	1994	9	14	16	19.5	25.5	28.5	
14	1995	9	13.5	18	19.5	25	28	
15	1996	9	14	19	20	25	28.5	
16	1997	9	14	21	20	25	28	
17	1998	9	15	22	20	26.5	29	
18	1999	9	16	23	21	32	32.5	
19	2000	9	16	24	22.5	32	33	
20	2001	9	16	24	23	32	33	
21	2002	9	16	24	23	32	33	
22	2003	9	16	24.5	23.5	32	33	
23	2004	9	16	25	24	32	33	
24	2005	9	16	26	24.5	32	33	
25	2006	9	16	27	25	32	33	
26	2007	9	16	27.5	25.5	32	33	
27	2008	9	16	27	26	32	33	
28	2009	9	16	28	26.5	32	33	
29	2010	9	16	29	27	32	33	

	I	J	K	L	M	N	O
1							
2	1988 GNP =						
3	4735.3						
4	GNP grows at						
5	2.40%	CBO Baseline	CBO Core	NCOS	AIAA	Ride (Lunar)	Ride (Mars)
6	GNP(88$)	%GNP	%GNP	%GNP	%GNP	%GNP	%GNP
7	4735.30	0.19	0.19	0.19	0.19	0.19	0.19
8	4848.95	0.19	0.23	0.20	0.26	0.24	0.24
9	4965.32	0.18	0.23	0.23	0.29	0.29	0.35
10	5084.49	0.18	0.25	0.24	0.32	0.30	0.37
11	5206.52	0.17	0.25	0.25	0.33	0.31	0.36
12	5331.47	0.17	0.27	0.27	0.36	0.48	0.53
13	5459.43	0.16	0.26	0.29	0.36	0.47	0.52
14	5590.46	0.16	0.24	0.32	0.35	0.45	0.50
15	5724.63	0.16	0.24	0.33	0.35	0.44	0.50
16	5862.02	0.15	0.24	0.36	0.34	0.43	0.48
17	6002.71	0.15	0.25	0.37	0.33	0.44	0.48
18	6146.77	0.15	0.26	0.37	0.34	0.52	0.53
19	6294.29	0.14	0.25	0.38	0.36	0.51	0.52
20	6445.36	0.14	0.25	0.37	0.36	0.50	0.51
21	6600.04	0.14	0.24	0.36	0.35	0.48	0.50
22	6758.45	0.13	0.24	0.36	0.35	0.47	0.49
23	6920.65	0.13	0.23	0.36	0.35	0.46	0.48
24	7086.74	0.13	0.23	0.37	0.35	0.45	0.47
25	7256.83	0.12	0.22	0.37	0.34	0.44	0.45
26	7430.99	0.12	0.22	0.37	0.34	0.43	0.44
27	7609.33	0.12	0.21	0.35	0.34	0.42	0.43
28	7791.96	0.12	0.21	0.36	0.34	0.41	0.42
29	7978.96	0.11	0.20	0.36	0.34	0.40	0.41

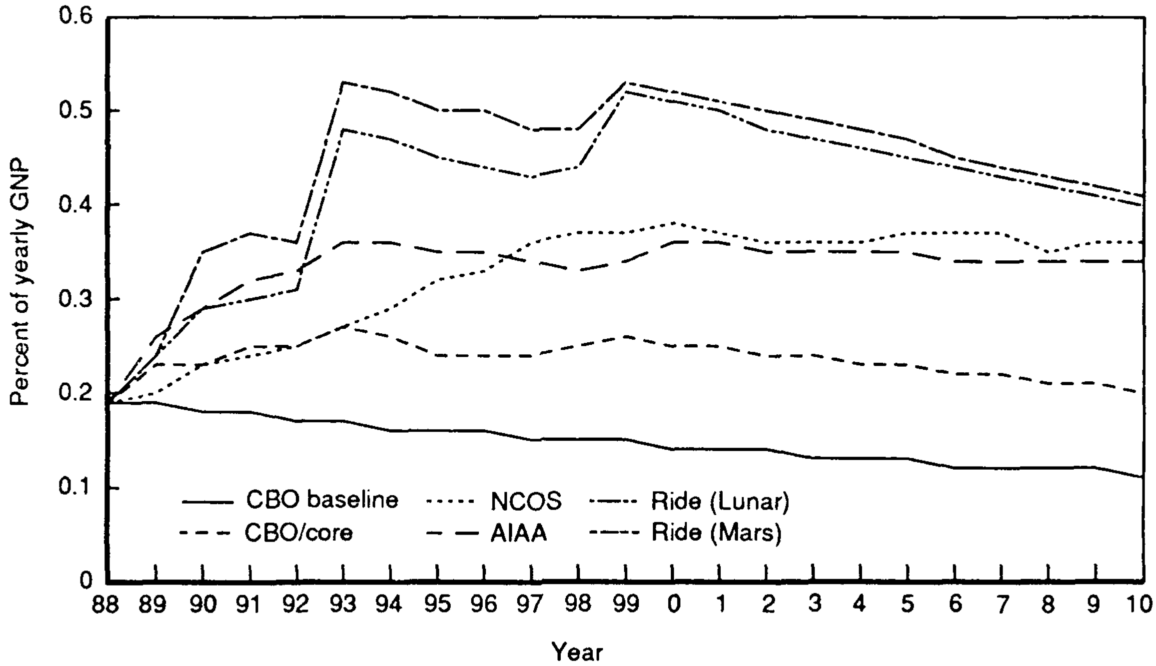
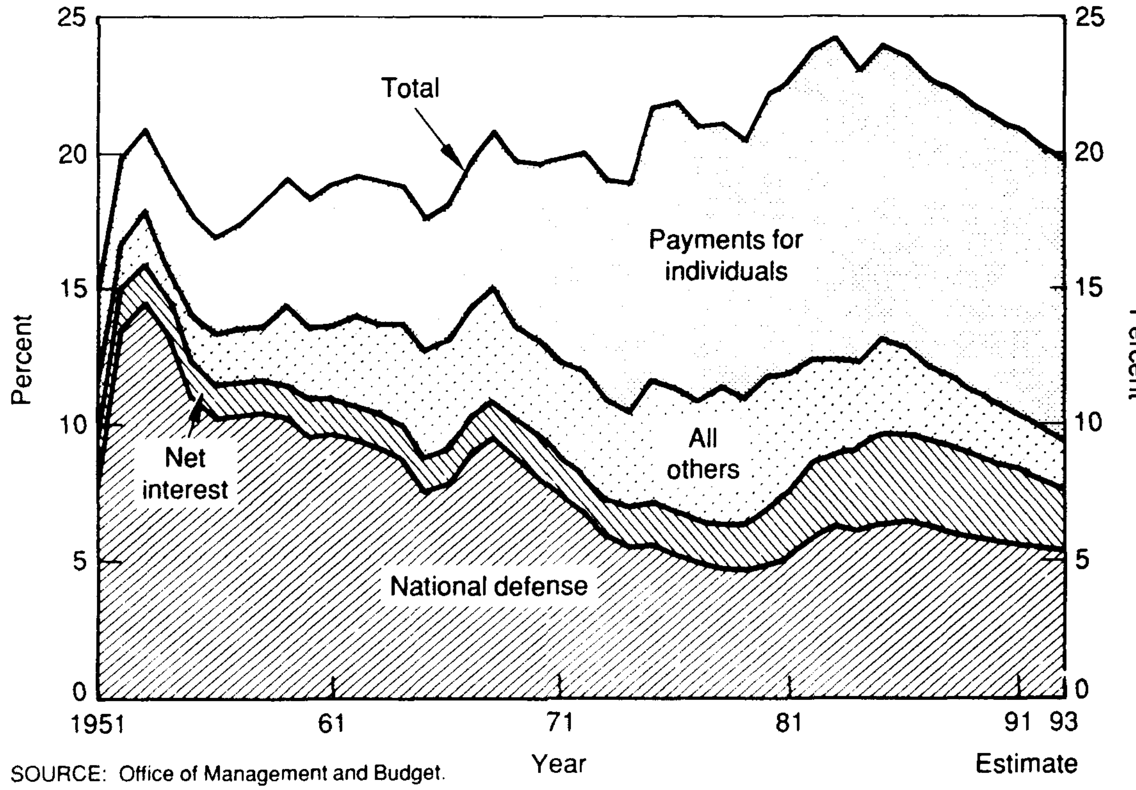
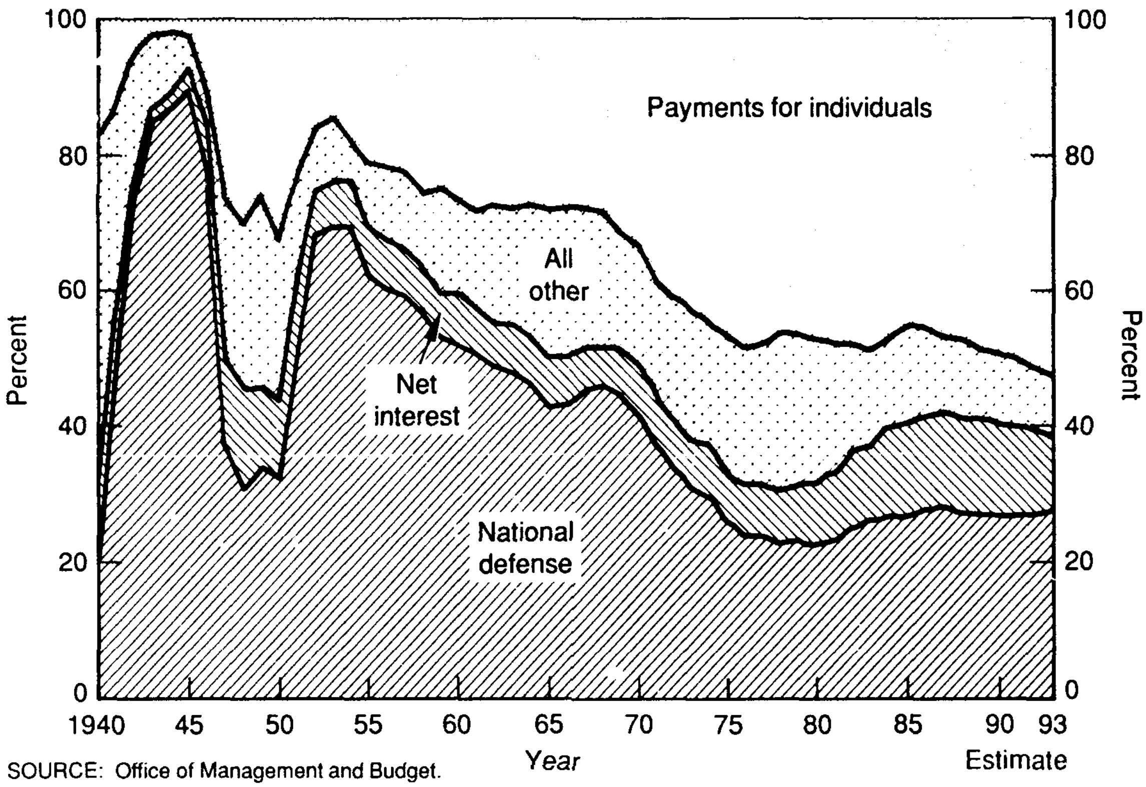


Fig. C.8—Potential civil space budgets as percent of GNP (2.4 percent real GNP growth per year)



SOURCE: Office of Management and Budget.

Fig. C.9—Federal government outlays as percentages of GNP



SOURCE: Office of Management and Budget.

Fig. C.10—Percentage composition of federal government outlays

would thus likely come at the expense of other government activities.[10] Tripling NASA's budget would take it to about 23 percent of outlays for these activities, severely squeezing other politically desirable activities. This assumes no real cuts in items such as Social Security and DoD outlays.

In summary, an ambitious expansion of civil space activity is likely to be possible in macroeconomic terms given past efforts. The crucial affordability issue is whether the political cost of compressing other government outlays can be met given the triple pressures of social spending, nonspace defense expenses, and interest on the national debt. An expanding military space effort will likely require tradeoffs not only with respect to other DoD programs, but with respect to civil efforts as well. The U.S. economy should be able to afford expanding efforts in space. It is less clear that the politics of the budgetary process can afford such expansions, whether civil or military.

[10]Competing activities would include housing and urban development, environmental protection, and consumer product safety which, with NASA, are all part of the jurisdiction of the House and Senate appropriations subcommittee on Housing and Urban Development and Independent Agencies.

Appendix D

SPACE TRANSPORTATION COSTS, RELIABILITY, AND RESILIENCY

D.1 INTRODUCTION

Prior to the loss of the Challenger, the shuttle was slated as the primary means of U.S. access to space. NASA had planned to phase out its use of expendable launch vehicles (ELVs), whereas the Department of Defense would continue to launch small numbers of ELVs to complement its use of the shuttle. However, since the loss of Challenger and several ELVs, space transportation plans have been extensively revised. New ELV production programs have been initiated and payloads have been moved off the remaining shuttles. The result is a more diverse mix of vehicles, with an expansion of the number of DoD ELV flights.

Appendix B examined the relation of launch costs per pound as a function of the cumulative payload mass deployed for individual vehicles. Left out of that discussion were considerations of vehicle reliability and the costs of the payloads placed at risk with each launch. These issues must be addressed to arrive at a full picture of the costs of space launches.

This appendix considers the cost and operability implications of the distribution of launch vehicles. Although many mixes of launch vehicles are capable of meeting the same levels of space traffic demand, those mixes may have very different associated costs and reliabilities. In assessing the total costs of launch vehicle "architectures," it is also important to ask what assurances exist that a given vehicle mix will successfully deliver its payloads to orbit. This involves more than the individual reliabilities of the launch vehicles. As discussed below, it is important to consider the "resiliency" of the total launch vehicle architecture, i.e., its ability to recover from accidents and standdowns.

D.2 PAYLOAD COSTS

Space transportation discussions are often dominated by concern over the cost of access to space. This is usually represented by a payload launch cost per pound to low Earth orbit (LEO), which currently ranges around $3000 per pound. Such figures are derived by dividing the cost of the launch vehicle by its payload capacity. In actuality, a vehicle is not often launched without a payload; thus the payload's cost might also be included in calculating the total cost of a flight.

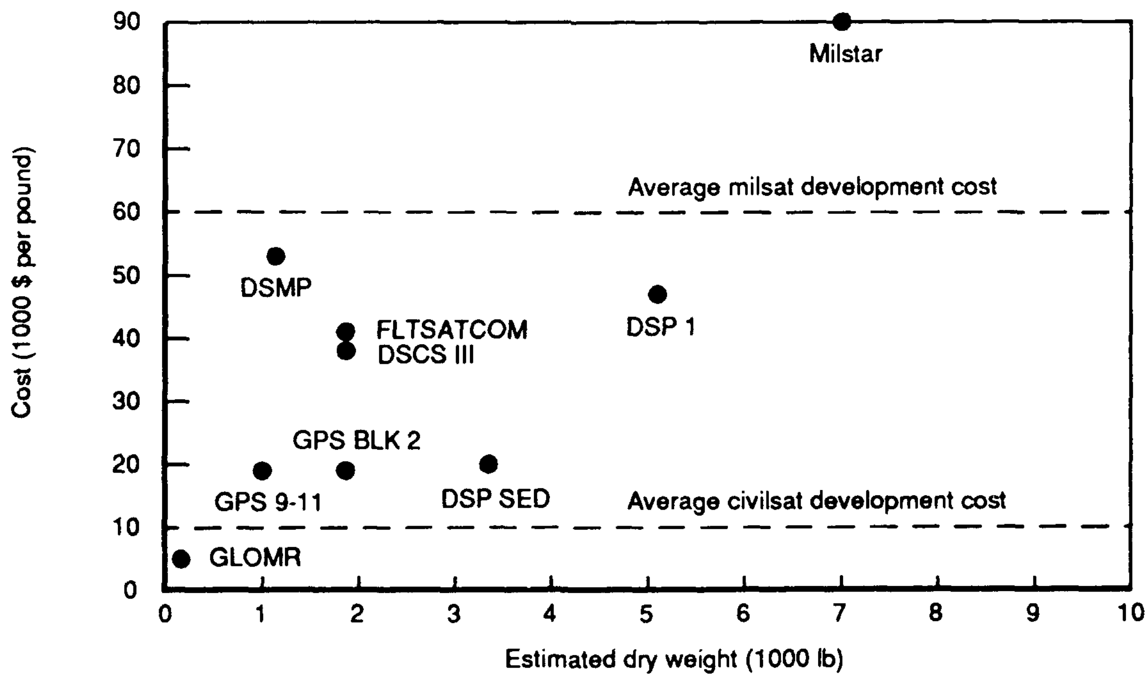
Data from the Aerospace Corporation, the Defense Advanced Research Projects Agency (DARPA), and the USAF Space Division suggest that payload costs per pound are substantial.[1] Figure D.1 depicts the the cost per pound of a variety of military satellites as a

[1] "Milstar Satellite/Booster Cost Reaches $1 Billion per Mission," *Aviation Week & Space Technology*, May 9, 1988, p. 27. Assuming 15 percent of costs for ground operations, a Titan-Centaur cost of about $218 million ($163 million + $55 million for the Centaur) and a satellite wet weight of about 10,000 lb leaves a cost per pound of about $63,200. Dry weight cost per pound is about $90,300. See also James W. Fanslow, *Spacecraft Costs for the Late 1980s*, MRJ Inc., Fairfax, VA, January 8, 1981; Col. Charles Heimach, "Case for Small Satellites," briefing, El Segundo, CA, Assistant DCS, Plans, USAF Space Division, April 26, 1987; and personal communication with Harry Bernstein, Systems Director, Space Transportation Plans and Architecture Directorate, Aerospace Corporation, May 1988. Internal estimates indicate that satellite development costs are about $60,000 per pound for military systems and $10,000 per pound for civilian systems. A weighted average of $35,000 per pound is often used as a typical number based on the assumption that payload mass is about 50 percent military and 50 percent civilian spacecraft. In comparison, the ALS Phase II mission model projects a split of 44 percent and 56 percent, respectively, between military and civil masses.

function of their dry weight. Although there seems to be a rough upward trend in payload cost per pound as a function of weight, firm conclusions are difficult to draw without data from classified programs.

The payloads in Fig. D.1 span a broad range of capabilities, including:

- GLOMR: Global Low-Orbit Message Relay satellite, a small test satellite developed by DARPA and launched from a shuttle Get-Away Special (GAS) cannister. Successfully operated for 14 months.
- GPS: Global Positioning System satellites. Also known as Navstars, these satellites have been developed in several blocks of increasing sophistication. Satellites 9–11 were part of the first block design.
- DSCS: Defense Satellite Communications System. Communications satellites placed in geosynchronous orbit for national security needs.
- FLTSATCOM: Fleet Satellite Communications System. Communications satellites serving the needs of the U.S. Navy.
- DMSP: Defense Meteorological Satellite Program. Polar orbiting weather satellites similar to their civilian counterparts operated by the National Oceanographic and Atmospheric Administration (NOAA).
- DSP: Defense Support Program. High-altitude satellites that provide worldwide warning of ballistic missile launches.
- Milstar: Military advanced communications satellite. A new generation, high-capacity, survivable communications satellite for national security needs.



SOURCE: *Aerospace Corporation*, DARPA, USAF, *Aviation Week.*

Fig. D.1—Military satellite costs

For comparison purposes, Fig. D.1 includes Aerospace Corporation estimates of satellite development costs for military and civil programs. Since satellites are usually produced in small numbers, it is not clear how much development and production costs would change if identical satellites were produced in large numbers. The GPS program has the largest current production run of satellites, with an operational constellation of 18 Navstars and three on-orbit spares. These satellites cost about $19,000 per pound.

For comparison with the above satellite costs, gold costs about $7500 per pound, the production cost of an F-16 fighter aircraft is about $1200 per pound, and space shuttle orbiter production costs are about $14,000 per pound.[2] It has been estimated that an SDI constellation of kinetic energy weapons (KEW) would cost about $12,000 per pound of spacecraft.[3]

D.3 COSTS OF UNRELIABILITY

The expense of developing and building payloads affects not only the available budget for space activity, but the costs of launch vehicles. The developments of launch vehicles and payloads are often thought of as separate activities, except where one has to consider how to technically interface the two for flight. The economic relationship between the two is, however, far closer.[4] When a launch is about to occur, the total cost of the flight involves the vehicle, its payload, *and* the risk of failure to which both are exposed.

Leaving aside issues of risk adversity, overhead costs, insurance pool limits, and so forth, the risk exposure per flight can be expressed as:

$$\text{risk exposure (\$)} = \text{(probability of failure) (cost of vehicle \& payload)}$$

or

$$\mathrm{RE} = (1 - \mathrm{R})\,(\mathrm{LVC} + \mathrm{PLC}) \tag{D.1}$$

where R = vehicle reliability, LVC = launch vehicle cost, and PLC = payload cost.

This should be considered a conservative estimate as it does not include the costs of recovering from an accident or the opportunity costs of a flight failure. At minimum, the value of the payload is the cost of procuring it.

As the cost of a payload or the chances of failure increase, the risk exposure increases. The cost of a payload can in turn increase as its cost per pound rises or if more payload mass is placed on a single flight. For 150,000 lb of payload, at $35,000 per pound, a single launch could place over $5 billion at risk. Figure D.2 plots risk exposure as a function of vehicle payload capacity (assumed fully used). Variations occur depending on assumptions as to vehicle reliability and payload cost per pound. Although launch vehicle costs have been neglected here, it is clear that the dollar value of risk exposure can be substantial. For a payload capacity of 55,000 lb, a reliability of .96, and a payload cost of $10,000 per pound, the risk exposure is about $20 million.[5]

[2]Heimach, op. cit., and Congressional Budget Office, *The NASA Program in the 1990s and Beyond*, U.S. Government Printing Office, Washington, D.C., May 1988, pp. 20–21.

[3]Peter Leonard, *Space Transportation Analysis*, L-Systems, Inc., El Segundo, CA, 2 March 1987, p. 26.

[4]See App. E for a discussion of the relationship or lack thereof between launch vehicle costs and payload development costs.

[5]Payload costs vary widely for specific missions. Some analysts distinguish between cost per pound of payload (e.g., the satellites being deployed) and the cost per pound of cargo (all mass in the payload bay, including upper stages, support cradles, etc.). The cost per pound of payload is usually greater than the cost per pound of cargo. Payload costs in this analysis should be interpreted as costs of the total mass in the payload bay.

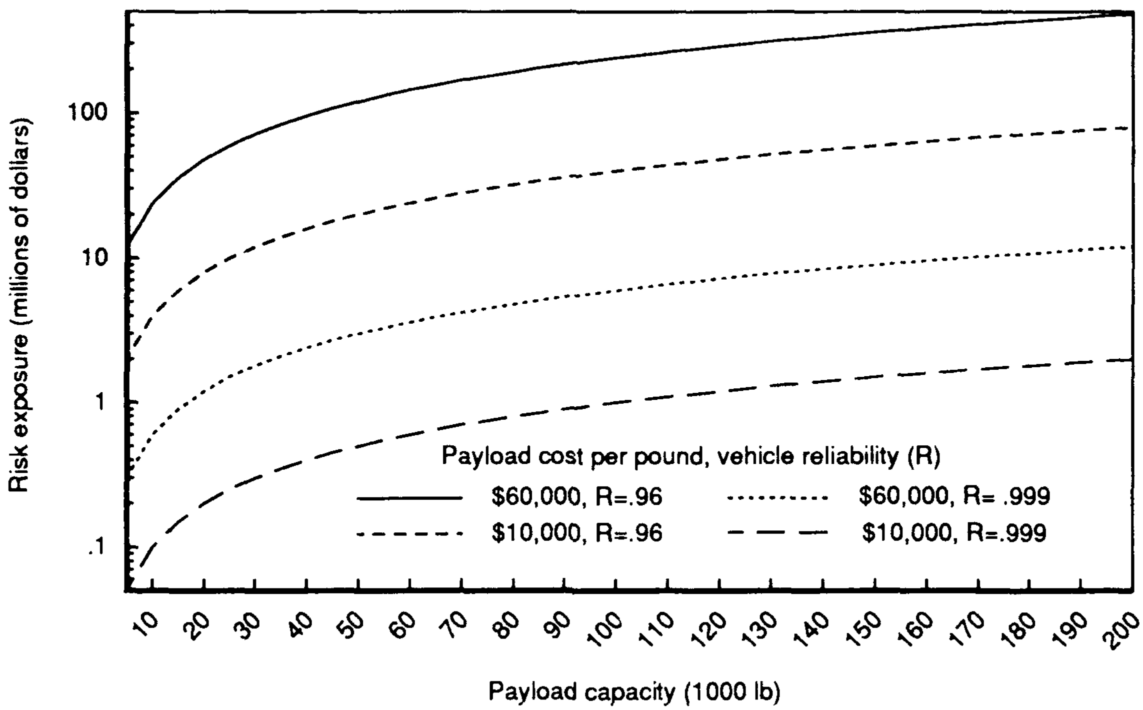


Fig. D.2—Risk exposure vs. payload capacity

If one is willing to bear a given level of risk, there is a relation between required reliability and the payload mass carried on a single vehicle. Not surprisingly, as payload size increases, vehicle reliability must increase. Figure D.3 shows three plots of varying payload size and vehicle reliability to give constant levels of risk exposure or "insurance cost." Assume a launch vehicle with a baseline payload capacity of 55,500 lb and a 96 percent reliability (for a .04 probability of failure). Figure D.3 shows how much the probability of failure must decrease for increases in payload capacity, assuming constant payload costs. An order of magnitude increase in payload size requires an order of magnitude increase in reliability for the same level of risk.

The cost of unreliability can easily exceed the cost of launch vehicle production and operations. *As long as payload costs per pound are several times that of launch costs per pound, high reliabilities will be required. If efforts to lower launch costs dramatically are successful, the relative importance of the payload's costs to each flight will increase further.* Unfortunately, the techniques and costs to achieve very high reliability (e.g., .99 and above) are not well understood. It is known that launch system life-cycle costs increase with higher reliability, and that such increases rise more steeply with each additional "9" of reliability.[6] Reliabilities that have been achieved to date are discussed next.

[6] Office of Technology Assessment, *Reducing Launch Operations Costs—New Technologies and Practices*, U.S. Government Printing Office, OTA-TM-ISC-28, Washington, D.C., September 1988, p. 27.

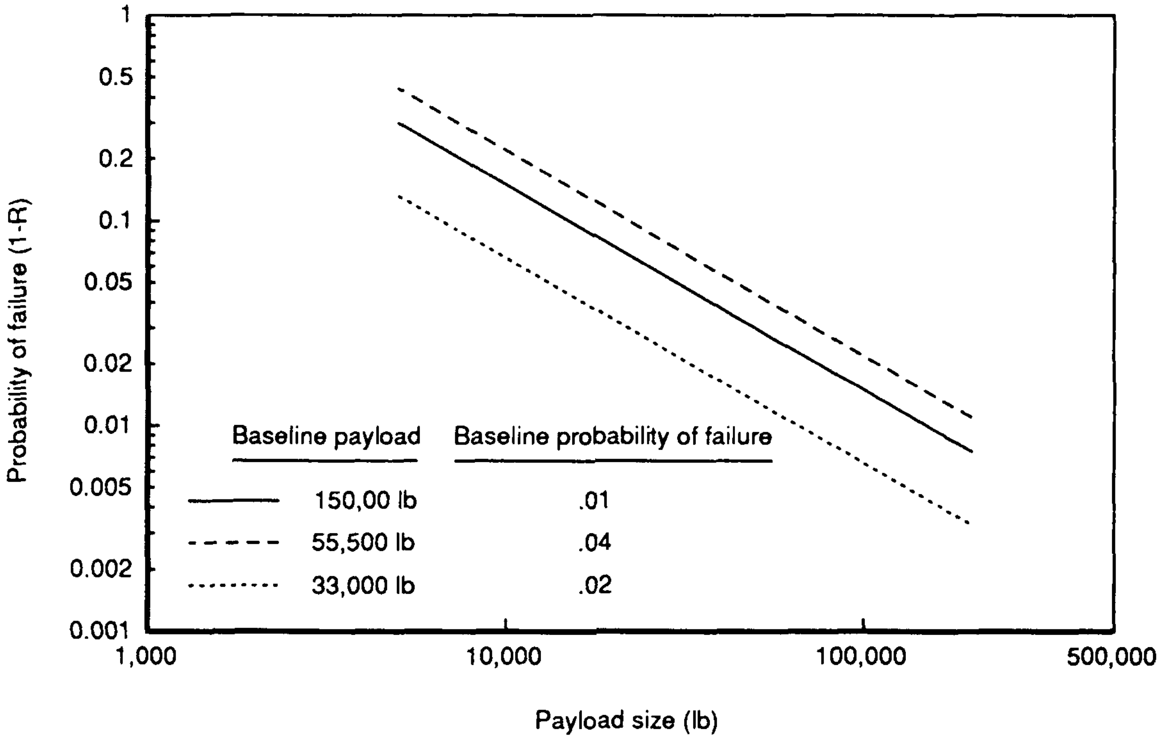


Fig. D.3—Constant insurance costs

D.4 HISTORICAL DATA ON LAUNCH VEHICLE RELIABILITIES AND STANDDOWNS

Given the importance of launch vehicle reliability and the disruptions that accompany a standdown, it is instructive to examine the historical record. Table D.1 was compiled from NASA data.[7] With the exception of the Saturn I and IB programs, the shuttle was the most reliable vehicle to date at 96 percent. The shuttle has also experienced the longest standdown of current (and historical) U.S. launch vehicles.

Figure D.4 depicts the data of Table D.1 in comparing cumulative vehicle reliability with the total number of launch attempts. It might be expected that as experience with a particular vehicle increased, its reliability would increase as well. Figure D.4 does seem to show such a trend, but it is not clear until beyond at least 50 flights. Very few launch vehicles have such long track records. Below about 50 launch attempts, reliabilities are scattered with no obvious pattern. The pattern is even less clear if 95 percent confidence limits for a normal distribution are applied. With only a few flights, the confidence limits are so broad as to be virtually useless for predicting the success of an additional flight.

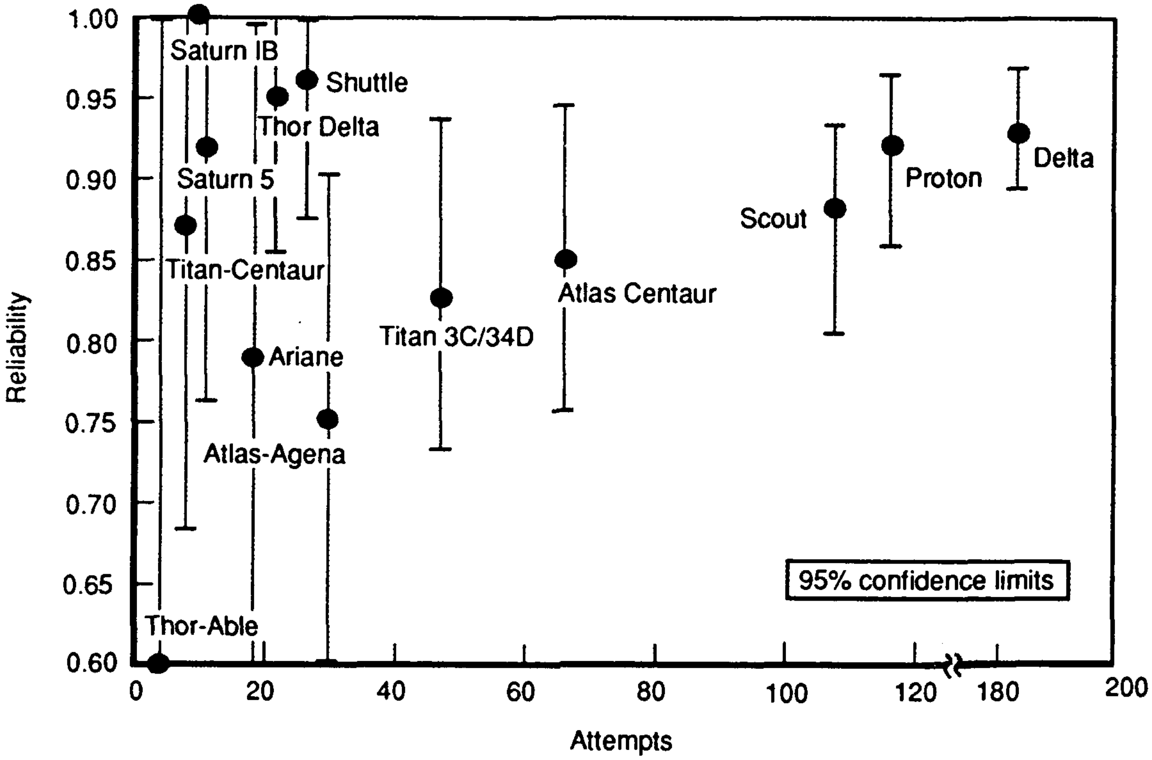
It appears that reliabilities above .95 are difficult but not impossible to achieve. The Delta launch vehicle has had a .98 reliability over the past 11 years. The last Delta loss was 1986, a year of many other failures. The question remains, however, as to what reliabilities

[7]NASA Headquarters, *NASA Pocket Statistics*, U.S. Government Printing Office, Washington, D.C., January 1988; Jerry Fitts, "Payload Backlog, Flight Rate Capability, Reliability and Downtime," briefing, Office of Space Flight, NASA Headquarters, Washington, D.C., November 5, 1987.

Table D.1

HISTORICAL DATA ON LAUNCH VEHICLE RELIABILITIES AND STANDDOWNS

	A	B	C	D	E	F	G
1							
2							
3			Total	Total	Cumulative	Last Failure	
4	As of	Launch System	Successes	Attempts	Reliability	Downtime (months)	
5	Nov.87	STS	24	25	0.96	31	
6	Nov.87	Titan 3C/34D	38	46	0.83	19	
7	Nov.87	Atlas Centaur	56	66	0.85	19	
8	Nov.87	Delta	169	181	0.93	4	
9	Nov.87	Scout	94	108	0.87	6	
10	Nov.87	Ariane(Fr)	15	19	0.79	16	
11	Oct.87	Saturn I	10	10	1.00	0	
12	Oct.87	Saturn IB	9	9	1.00		
13	Oct.87	Saturn V	12	13	0.92		
14	Oct.87	Thor-Able	3	5	0.60		
15	Oct.87	Thor-Agena	12	13	0.92		
16	Oct.87	Thor-Delta	20	21	0.95		
17	Oct.87	Titan Centaur	7	8	0.88		
18	Oct.87	Atlas-Agena	24	32	0.75		



SOURCE: NASA, January 1988.

Fig. D.4—Launcher reliability

might be expected from newly developed vehicles? It would seem that achieving a .98 reliability or better starting from a vehicle's first launch is a serious challenge.

A net vehicle reliability of .99 imposes high reliability requirements through a launch vehicle's major systems. One example breakdown for a hypothetical new launch vehicle was supplied by Martin Marietta, as shown below.[8]

Subsystem	Allocated Reliability to Achieve System Reliability of 0.99
Liquid engine subsystem	.998393
Solid engine subsystem	.992989
Structure	.999598
Avionics	.999799
Electrical	.999799
Ordnance	.999900
Pressurization/hydraulics	.999699
Thrust vector control	.999900
Ground support equipment	.999900

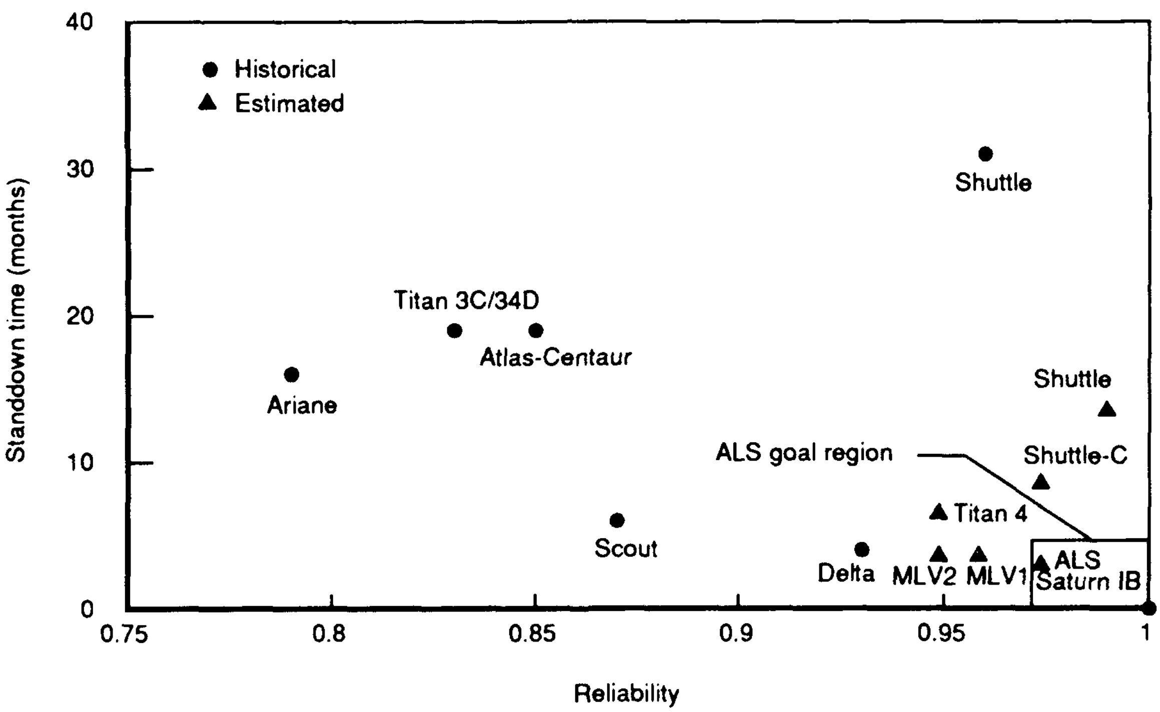
Needless to say, these levels of subsystem reliability have yet to be demonstrated. For example, obtaining an avionics reliability of .995 would be a significant achievement.

[8]J.W. McCown, "Future Launch Vehicle Development and Technology Requirements," briefing, Advanced Programs, Martin Marietta, Denver, CO, October 6, 1987.

In the event a launch failure does occur, how long might vehicles of that type have to stand down? Figure D.5 compares the length of the last standdown period with the cumulative reliability of several vehicles from Fig. D.4. With the exception of the shuttle, there appears to be a trend toward shorter standdowns (about six months) as vehicle reliability (and net experience) increases.

How long might standdowns be for a newly developed system? If the standdown was from a design flaw, the vehicle might be down a long time while changes are made and qualified. If the standdown was due to a process flaw, the downtime might be less. The design of the vehicle would be sound, but safeguards would be introduced to ensure it is prepared as planned. The shortest standdown could be expected from operational flaws, such as missing a weather prediction and launching outside of allowable conditions.[9] The shaded area of Fig. D.5 indicates the system reliability and standdown time objectives for the Advanced Launch System.[10] The triangles indicate the reliability and standdown estimates used in the main text for flights during 1990–2010. As discussed in Sec. 4.5, these estimates represent goals to be achieved and may be optimistic.

NASA has recognized that building in launch margin to deal with accidents and standdowns is a necessary precaution. However, buying margin is expensive in terms of extra vehicles and ground capacity. As Fig. D.6 makes clear, long downtimes and low reliabilities lead to desired capacities far in excess of planned payload flight rates.[11] Figure D.7 shows a NASA estimate of the margin needed if reliabilities above .97 and standdowns



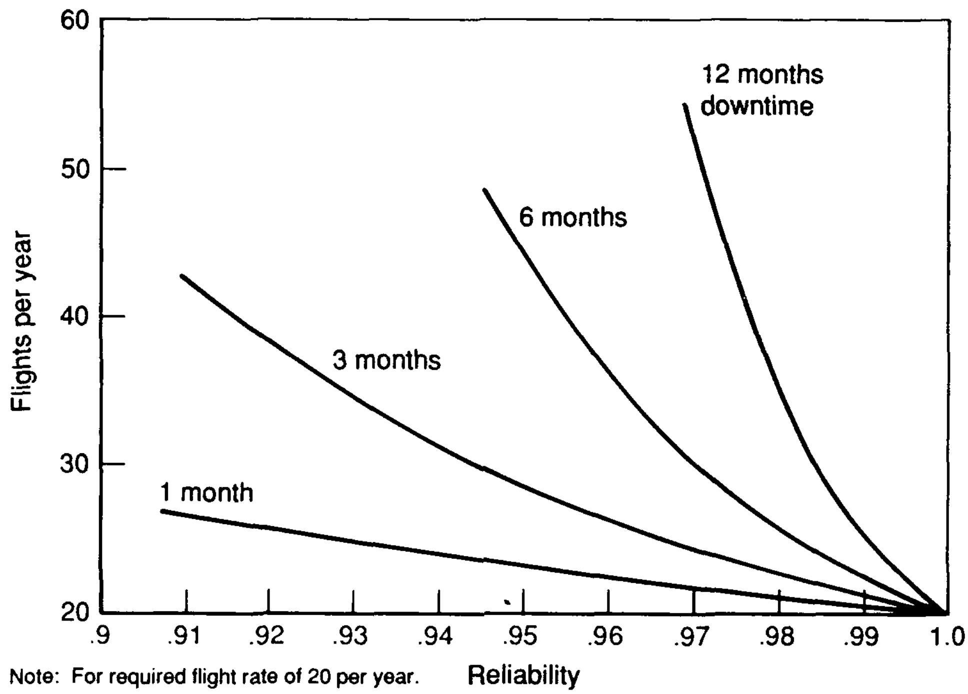
SOURCE: NASA, January 1988.

Fig. D.5—Standdown times vs. vehicle reliability

[9]Some critics of the long standdown of the shuttle program contended that the O-ring failures should have been treated as operational flaws (i.e., don't launch when it is too cold) as opposed to a design flaw (necessitating a full redesign and qualification effort).

[10]Office of Technology Assessment, op. cit., p. 16.

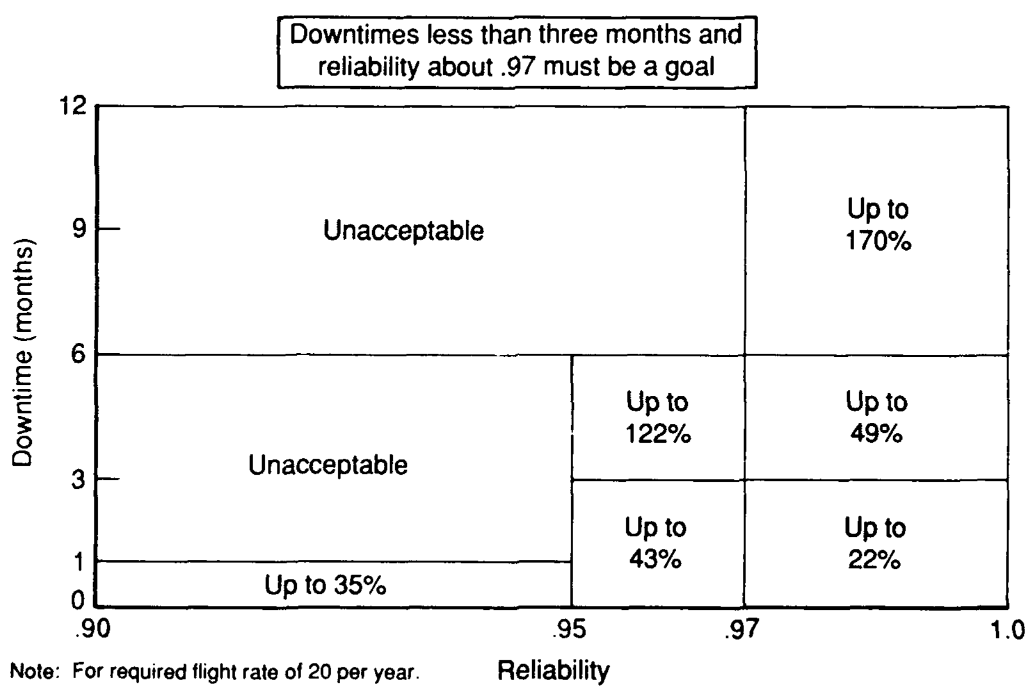
[11]Fitts, op. cit.



Note: For required flight rate of 20 per year.

SOURCE: NASA Office of Space Flight.

Fig. D.6—Flight rates vs. launcher reliabilities and downtimes



Note: For required flight rate of 20 per year.

SOURCE: NASA Office of Space Flight.

Fig. D.7—Surge rates vs. launcher reliabilities and downtimes

below three months could be achieved. Even with this achievement, significant excess capacity would still be maintained to service backlogs from the remaining standdowns. Later subsections will discuss recovering from standdowns and alternatives to buying launch margin.

D.5 CALCULATING TOTAL FLIGHT COSTS

Cost estimation is a difficult topic, especially for high-technology systems such as launch vehicles and payloads. However, many of the crucial relationships affecting system costs can be investigated using simple parametric relations. Such relations are often sufficient to identify major system tradeoffs, even if inadequate for detailed budget planning.[12]

A total mass M (pounds) was assumed to be flown over a period of time (years). All mass is flown to low Earth orbit, including upper stages and support cradles as well as the payloads themselves. For simplicity, payloads were assumed to be infinitely divisible and have no manifesting constraints by payload size, function, or destination. Each flight was thus manifested to 100 percent of its upweight capacity. Such assumptions take demand as a given and are inelastic with respect to total costs. This is obviously not true, but a reasonable approximation when payloads are primarily government owned rather than privately owned.

A simple estimate of the total cost to fly a given amount of mass covers three categories: launch vehicle costs, payload costs, and risk exposure. This estimate is made below for a single launch vehicle type, but it can be extended to any number of vehicles with their own demand schedules. Cooperation among vehicles in flying the same payloads is more complicated and will be discussed with estimates of system resiliency.

$$TC = LVC + PLC + RE \tag{D.2}$$

where
TC = total cost
LVC = launch vehicle costs
PLC = payload costs
RE = risk exposure

and

$$N = M/PLB(R) \tag{D.3}$$

where
N = number of flights required
M = total mass to LEO
PLB = effective vehicle upweight capacity
R = launch vehicle reliability

Each launch vehicle can be characterized not only by its effective upweight capacity, but by its reliability and the cost per pound of its total payload. This entails an assumption that the cost per pound remains constant as payloads are flown, and thus means neglecting learning curve effects from gained experience and any amortization of development costs

[12]Strategic Defense Initiative Organization, Cost Analysis Program, Vol. 3, Cost and Technical Factors, Washington, D.C., April 1987, especially Sec. 9, "Estimation of Space Transportation Costs"; and Gene H. Fisher, *Cost Considerations in Systems Analysis*, The RAND Corporation, R-490-ASD, December 1970, especially Chap. 7, "Cost Models."

(unless they are assumed included in the average cost per pound figure). In more general terms, launch cost per pound is also a function of vehicle reliability and payload capacity, but all three terms are assumed to be exogenous.

$$LVC = (LVCP)(PLB)(N) \tag{D.4}$$

where LVCP launch cost per pound

Payload costs are substantial, as shown earlier. It has often been asserted that payload costs are dependent on launch vehicle costs—that is, if launch costs drop, then payload costs will drop as well, assuming all else equal.[13] This assertion is plausible, but evidence is scarce and contradictory. Again, payload costs per pound are assumed as given.

$$PLC = (PLCP)(PLB)(N) \tag{D.5}$$

where PLCP = payload cost per pound

Risk exposure from Eq. (D.1) can be reexpressed using Eqs. (D.4) and (D.5) above.

$$RE = (1 - R)[LVCP(PLB)N + PLCP(PLB)N] \tag{D.6}$$

Putting Eqs. (D.4), (D.5), and (D.6) together into Eq. (D.2) and substituting in Eq. (D.3), total cost becomes

$$TC = (M/R)[(LVCP + PLCP)(2 - R)] \tag{D.7}$$

This expression is largely true for expendable systems, but is only an approximation for reusable or partially reusable vehicles. In those cases, additional terms should be added to cover replacement and depreciation costs in the indemnified amount. In the case of the shuttle, a term can be added to cover the risk of losing the reusable orbiter. Equation (D.7) would then become

$$TC = (M/R)[(LVCP + PLCP)(2 - R)] + (1 - R)(LVRC) \tag{D.8}$$

where LVRC = reusable element replacement cost

The replacement cost of a shuttle orbiter is about $2.1 billion in 1988 dollars.[14]

[13]The argument goes that if access to space were cheaper, then payload costs would drop as payloads could use cheaper components. Losses from decreased reliability could be made up by more frequent space-based servicing and replacement launches.

[14]The cost of replacing the Challenger is about $1.75 billion plus an addition $400 million that had already been spent for major structural spares before the accident. This does not include the cost of three new main engines at a cost of about $100–$120 million in total. See "New Space Shuttle is Taking Shape," *New York Times*, October 7, 1988, p. 16.

D.5.1 Examples of Total Cost Calculations

In the simple case of a single flight and neglecting replacement costs of reusable elements, Eq. (D.7) reduces to simply

$$\text{Cost per flight} = (\text{LVCP} + \text{PLCP})(2 - \text{R})(\text{PLB}) \tag{D.9}$$

Applying this equation to current launch vehicles and assuming payload costs of $10,000 per pound, total costs per flight figures range from $17 million to $800 million. For current vehicles, Fig. D.8 shows the percentage of total cost attributable to the vehicle, payload, and unreliability risk, respectively. Figure D.9 uses the same equations, with respect to potential launch vehicles. The results depend on the particular values chosen for each vehicle, which are listed in Table D.2 below.

The major point of Figs. D.8 and D.9 is that payload costs are a dominant part of current flight costs and will become even more important if launch costs drop. A secondary point is that low vehicle reliabilities will generate noticeable risk exposures that should be taken into account in calculating costs per flight. This is particularly important when reusable elements are involved. In Fig. D.9, costs per flight for the shuttle are shown with and without the risk exposure of the orbiter's replacement cost (i.e., Eq. (D.8) was modified for a single flight cost). For many vehicles, however, the risk exposure is a negligible percent of total costs.

Figure D.10 shows the effect of lower vehicle reliability on the total cost of deploying a given one million pounds of payload to low Earth orbit. This plot comes from Eq. (D.7) and assumes a single fleet of expendable vehicles. Gaining additional reliability would appear to be worth a few hundred million dollars.

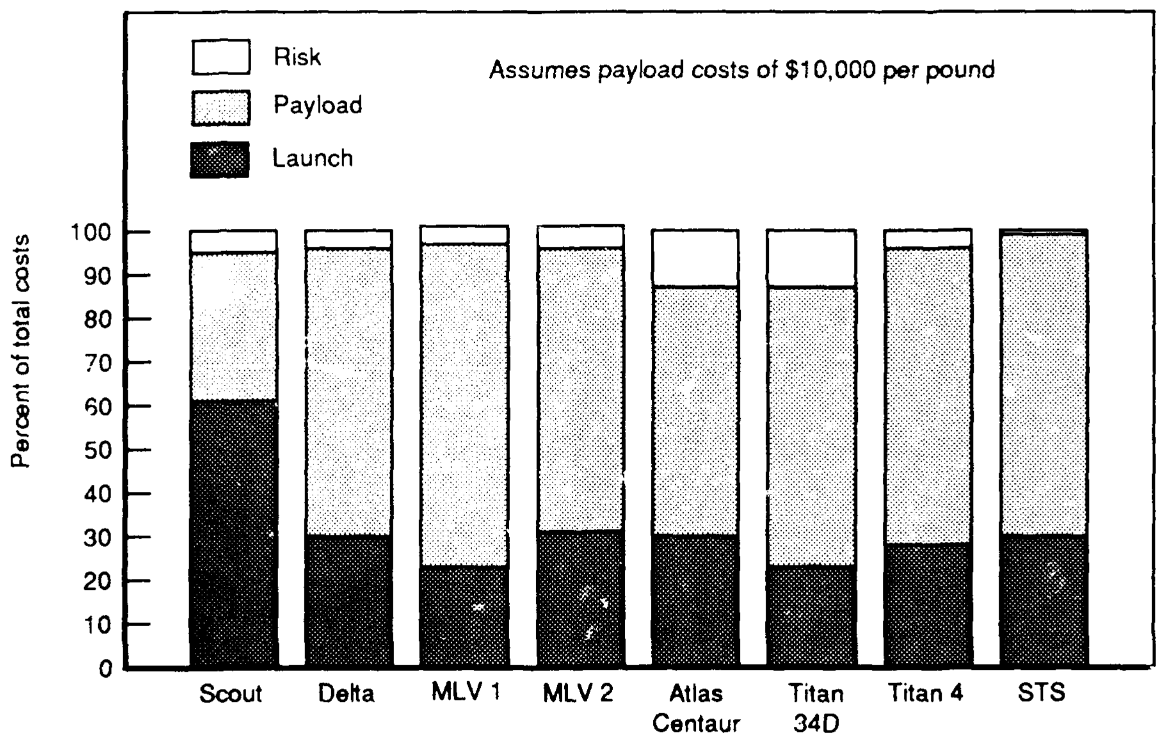


Fig. D.8—Launch, payload, and risk costs per flight (current vehicles)

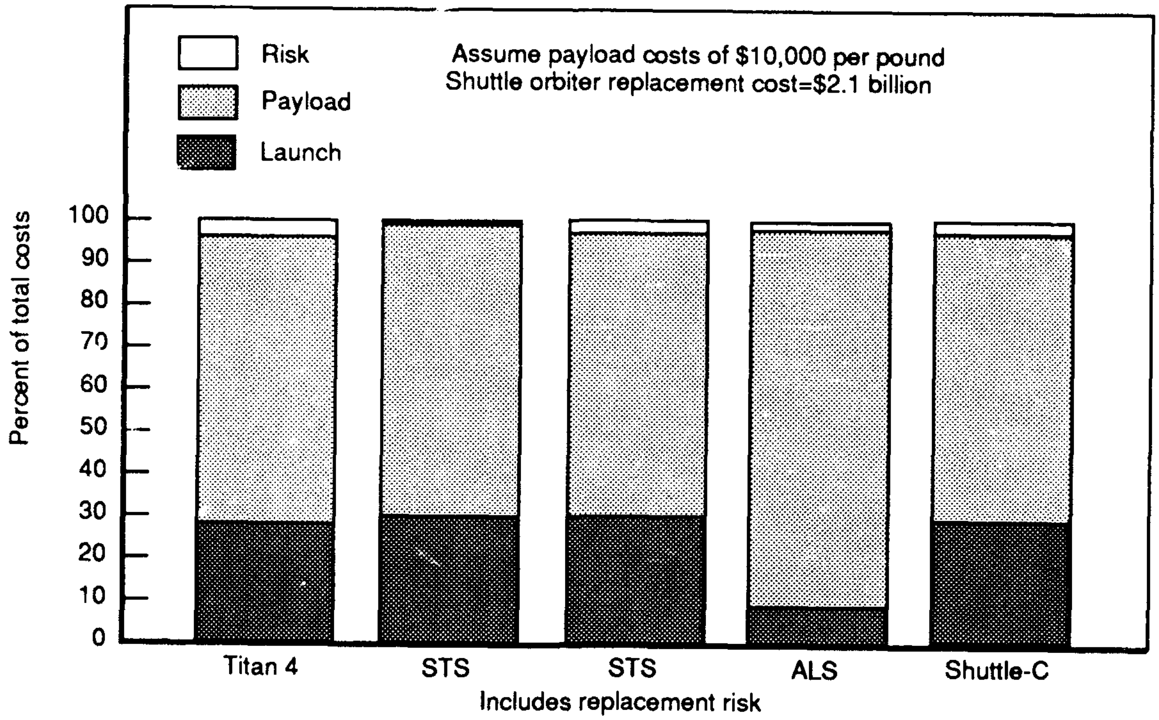


Fig. D.9—Launch, payload, and risk costs per flight (proposed vehicles)

Table D.2

EXAMPLE LAUNCH COSTS PER POUND AND RELIABILITIES

Vehicle	Launch Cost per Pound	Reliability
Scout	$18,000	.95
Delta	$4,487	.96
MLV 1	$3,070	.96
MLV 2	$4,765	.95
Atlas Centaur	$5,221	.85
Titan 34D	$3,600	.83
Titan 4	$4,169	.95
STS	$4,414	.99
Shuttle-C	$4,333	.98
ALS	$1,000	.98

D.5.2 Buying Margin vs. Cooperative Launch Systems

In the above calculations, it was assumed additional flights could be bought to make up for losses. This is not always possible in reality. There are physical constraints on achievable flight rates set by production facilities, ground processing times, and flight control facilities.

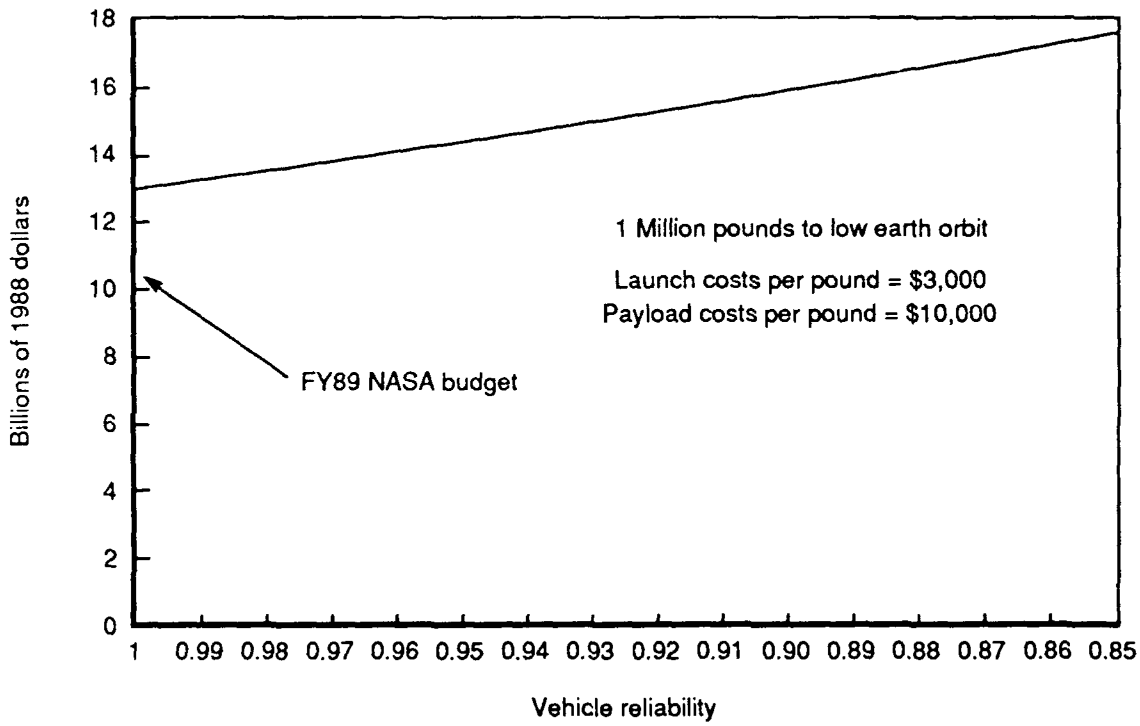


Fig. D.10—Total costs vs. vehicle reliability

A simple way to look for possibly "excessive" flight rates is to calculate the flight rates implied by "buying margin" as done above.[15]

$$F = FN(1-R) \tag{D.10}$$

$$TDT = FN(1-R)DT \tag{D.11}$$

$$OT = T - TDT \tag{D.12}$$

where
F = number of failures
FN = flights needed (with no failures)
DT = average vehicle downtime
TDT = total downtime
T = total time of interest
OT = operational time

Desired flight rates, FD, are calculated as the ratio of flights needed to the available operational time.

$$FD = FN/OT \tag{D.13}$$

or

$$FD = N/[T(R) - N(1-R)DT] \tag{D.14}$$

[15]Fitts, op. cit.

Equation (D.14) shows that as reliability declines and downtimes lengthen, the required flight rate increases steeply to make up for the losses. It also assumes the downtime is some fraction of the total time available. Obviously, a vehicle can be down so long that it can never make up its backlog. The cost of having margin over having none at all is simply the risk exposure (RE) from Eq. (D.6).

$$RE = (1 - R)[LVCP(PLB)N + PLCP(PLB)N] \qquad (D.15)$$

If vehicle reliability is 1, the cost of margin disappears. Conversely, if it is low, the cost goes up. If the flight rate cannot be increased enough and if payloads cannot wait, then alternative means of getting to space are required. The cost of margin may also rise so high that alternatives are desired. This would mean off-loading payloads onto other vehicles which then act as complementary or replacement launchers.

The total cost of having two cooperating systems is the sum of the total costs of the two systems. This assumes that there is no sharing or competition for common resources that affect the launch cost per pound. Even if there is, one can simply set different costs as part of the exogenous input.

$$\begin{aligned} TC = {} & (M_1/R_1)[(LVCP_1 + PLCP)(2 - R_1)] \\ & + (M_2/R_2)[(LVCP_2 + PLCP)(2 - R_2)] \end{aligned} \qquad (D.16)$$

where $$M = M1 + M2 \qquad (D.17)$$

Assuming both systems are launching the same type of payload, the payload costs per pound on both vehicles are the same. The difficult question is not how much a complementary system costs, but how to divide payloads among them. At least four factors influence this:

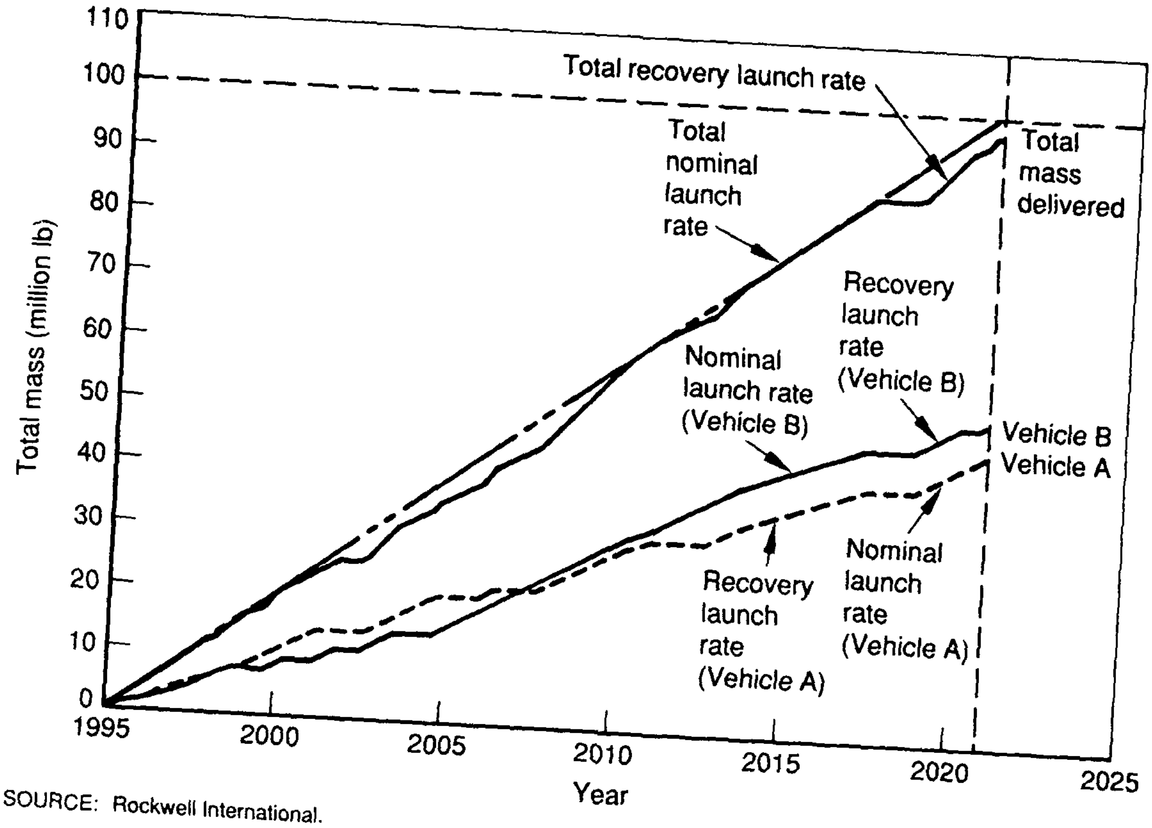
- The percent of payload mass which is fact compatible with both vehicles;
- The exchange ratio between the two (i.e., how many of vehicle A equals a vehicle B);
- The cost of dual compatibility to the payloads;
- The degree of intersystem dependency, that is, the degree to which R_A and R_B are not independent of each other.

Vehicle failures in cooperating systems would be linked to the degree they shared common technologies and processes.

One vehicle may be generally preferred to another in that it is cheaper to use, up to its flight rate limit. The second vehicle takes over only after the first is filled to capacity. In a more truly complementary mode, both vehicles would fly at a nominal rate below their full capacity. In the event one or the other vehicle has an accident and must stand down, the remaining vehicle begins flying dual-compatible payloads at full capacity. It is crucial that the remaining vehicle be unaffected by the first standdown, that dual-compatible payloads exist, and that the remaining vehicle can exceed its nominal flight rate to make up the backlog during standdown.

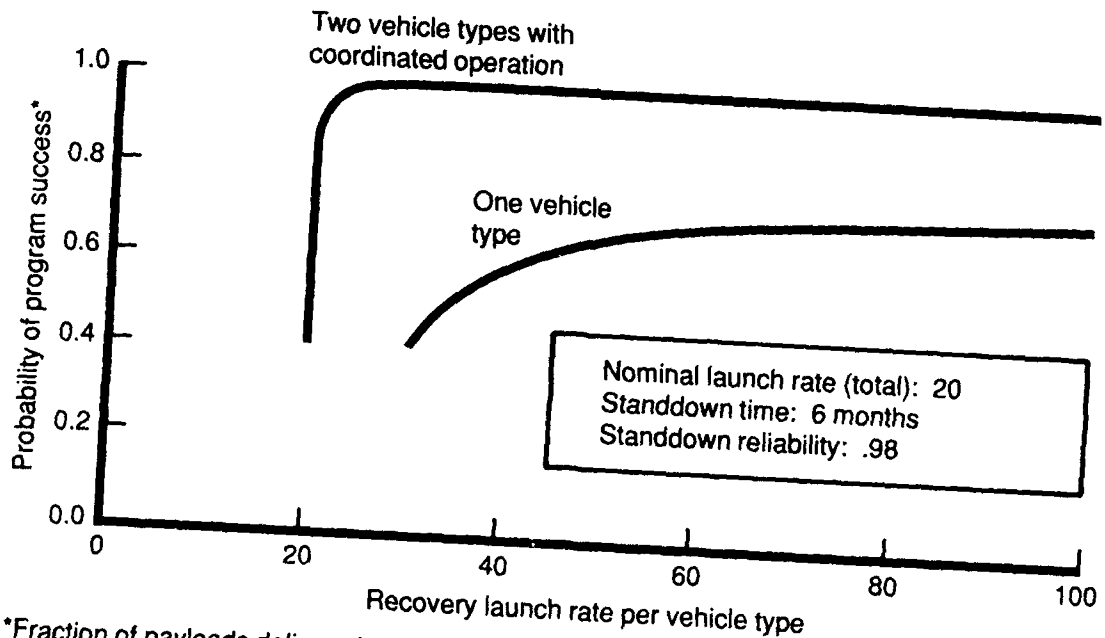
Figure D.11 depicts a Monte Carlo simulation of cooperating launch vehicles under assumptions that the payloads are fully dual-compatible and the exchange ratio is 1:1.[16] Figure D.12 shows the fraction of payloads delivered on schedule as a function of the recovery

[16]Rockwell International, *Space Transportation Architecture Study, Final Report, Vol. 2, Architecture Sensitivity Analyses*, STS Division, Downey, CA, November 16, 1987, pp. 78–89.



SOURCE: Rockwell International.

Fig. D.11—Analysis of mixed fleet performance is expansion of individual vehicle analysis



*Fraction of payloads delivered on schedule

SOURCE: Rockwell International.

Fig. D.12—High recovery launch rates required for single vehicle type

flight rate of each vehicle. The single vehicle case, with high recovery launch rates, is essentially the case of buying margin as described above. Even with extreme increases in the recovery flight rate, many of the payloads do not get flown on schedule. In the case of two vehicles with coordinated operations, large backlogs do not develop during standdowns. This results in much smaller increases in the recovery flight rate above nominal to meet payload launch requirements.

Whether the additional fixed costs (included in the launch cost per pound) of having two vehicles and dual-compatibility (included in the payload cost per pound) are worthwhile is a separate question. It depends on the opportunity costs of not flying on time as well as how likely a serious standdown is for each vehicle. The ability of a launch vehicle system to recover from an accident is often termed its "resiliency" and is the next subject.

D.6 Space Transportation System Resiliency

In the wake of the Challenger accident and as the United States moves toward a more diverse launch vehicle mix, assuring operational success has received renewed attention. The previous emphasis on reducing launch costs with high usage of a single or limited number of launch vehicles assumed a level of operational reliability that did not materialize. The result was a major disruption in launch schedules and a backlog of payloads that will likely last until 1992.[17]

D.6.1 Shuttle Reliability

What are the odds are of losing another shuttle orbiter? The past figure of 96 percent reliability is based on only 24 flights and does not constitute a sufficient data base to project future reliability. The curves in Fig. D.13 show the result[18] of varying assumed shuttle reliability between .96 and .995, as a function of cumulative flights. The probability of no orbiter losses drops as the cumulative number of launches increases and the individual flight reliability decreases. An accident would usually lead to the loss of the vehicle in the case of an ELV, but the situation is more complicated for the shuttle. Notwithstanding the Challenger loss, the shuttle system has more options for aborting a mission intact than an ELV. It is also subject to other (non-ELV like) risks such as being transported back to Cape Kennedy after landings at Edwards Air Force Base. It is thus hard to say that a particular mission reliability is also the chance of losing an orbiter.

Figure D.14 recasts the graphs of Fig. D.13 in terms of years and flight rates per year. If the yearly flight rate is lowered, the argument goes, the date of an orbiter loss may be pushed off into the future. If losses are delayed long enough, time is available to build better replacement vehicles. The clear message of Fig. D.14 is that even with large increases in reliability (from .96 to .99) the flight rates now contemplated (12–14 flights per year) will lead to a 50 percent chance of an orbiter loss by 1995–1996. This assumes a major accident is the same as an orbiter loss and that conserving orbiters is preferable to gaining more flight experience (and risking losses) with them.

No orbiter losses were assumed in the assessment of launch vehicle options, although situations may occur where payloads are lost or the shuttle fleet stands down after a serious accident. The loss of another orbiter would be a major blow to the United States (see Sec. 7.1.1, "Events Which Might Alter the Conclusions").

[17]NASA, *Payload Flight Assignments—NASA Mixed Fleet*, Office of Space Flight, Washington, D.C., March 1988.
[18]L-Systems, Inc., *Space Transportation Analysis—Summary Document*, El Segundo, CA, 2 March 1987.

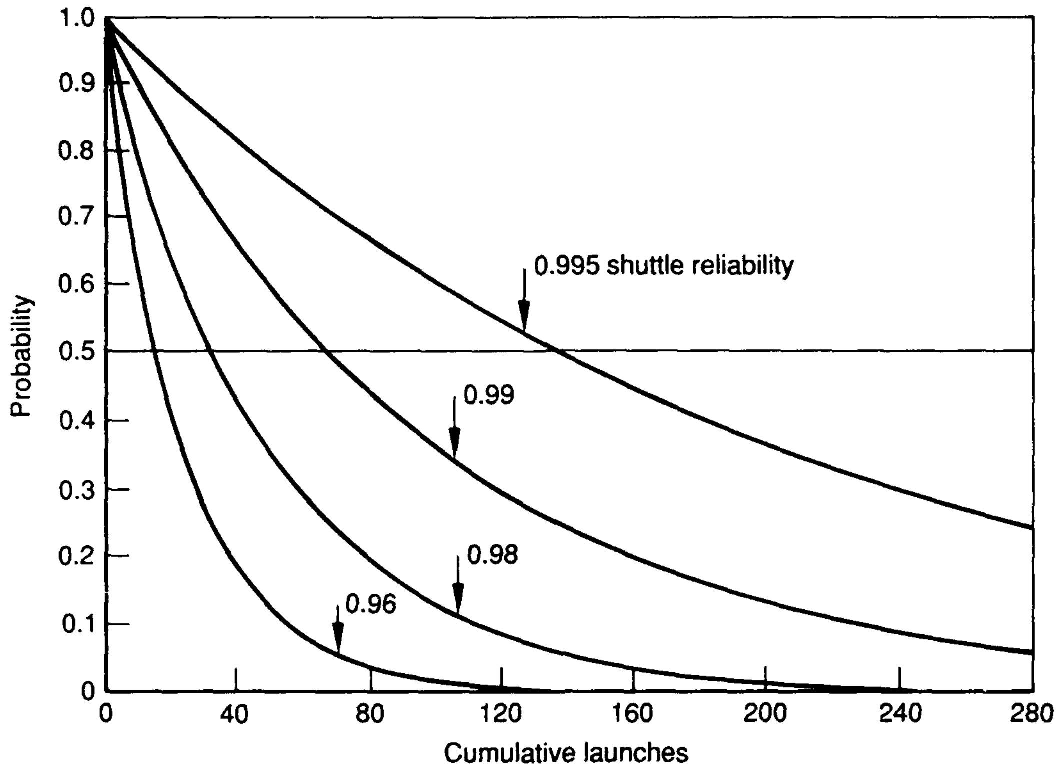


Fig. D.13—Probability of no orbiter losses vs. cumulative launches

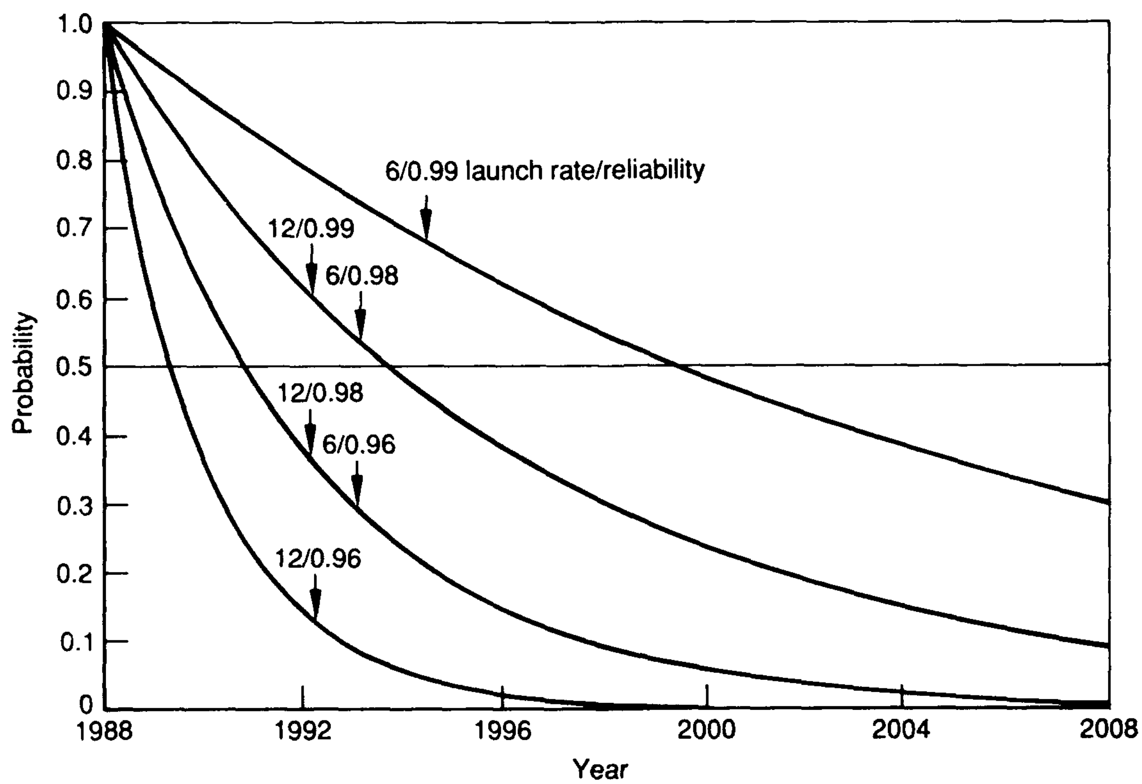


Fig. D.14—Probability of no orbiter losses vs. time

D.6.2 Calculating Resiliency

Reliability alone is not the best measure of a launch system's operational effectiveness. Other factors such as the length of standdown times, number of backlogged payloads, and maximum flight rates need to be considered as well. The concept of resiliency was developed to assess the robustness of launch vehicle systems. In the preliminary requirements document for the Advanced Launch System, resiliency is defined as:

> . . . the ability of the system to readily recover from the effects of flight failures and resulting standdown times. Resiliency can be expressed as a sufficiently high probability of recovering from the effects of a failure before suffering another failure. A resilient system has sufficient launch rate surge capability to ensure that payload backlogs due to post-failure standdowns will not grow unbounded over time . . .[19]

In addition to resiliency, analysts at the Aerospace Corporation have defined availability and reliability as important determinants of overall launch system operability.[20] Availability is the fraction of time the launch system is operational. All these factors are related to each other and achieving high values for all of them is obviously helpful. It is clear what reliability and availability commonly mean, but resiliency requires more definition to be a useful parameter.

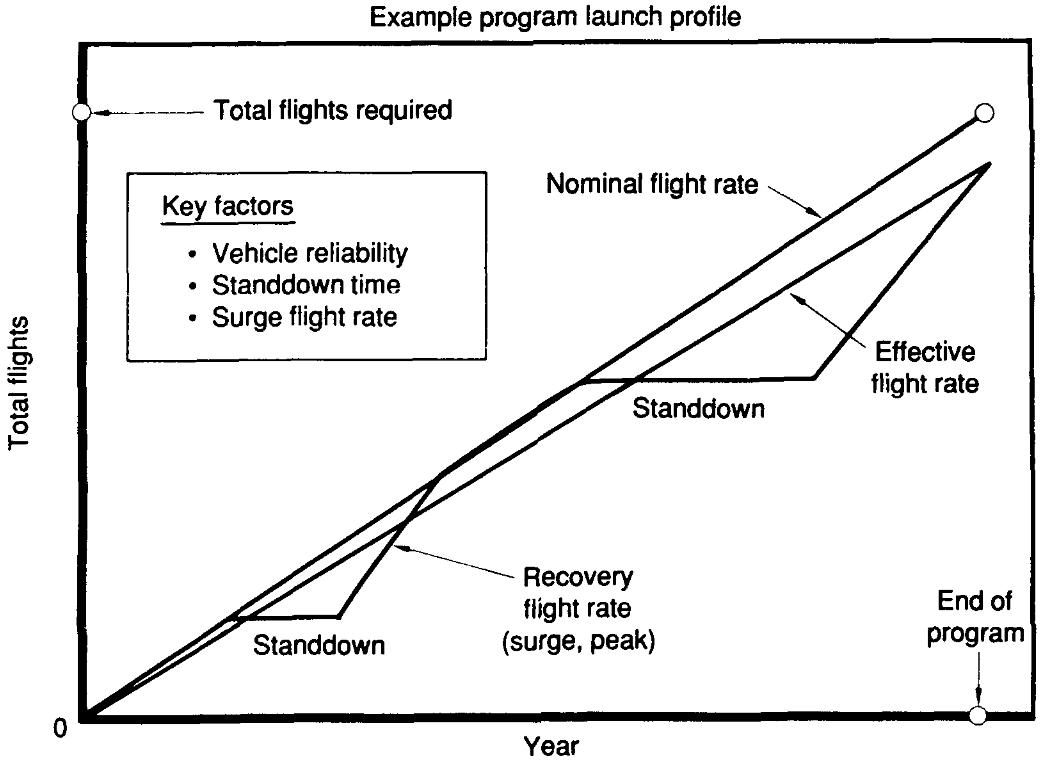


Fig. D.15—Resiliency raises effective flight rate

[19]USAF Space Division, *Advanced Launch System Requirements Document (Preliminary)*, SD-ALS-R-SRD-v1.00, El Segundo, CA, March 3, 1988, p. 14.

[20]Harry Bernstein and Dwight Abbott, "Space Transportation Architecture Resiliency," briefing, the Aerospace Corporation, El Segundo, CA, August 1987.

Consider the example launch program shown in Fig. D.15. Accidents occur in attempting to fly at a nominal flight rate over a period of years. Some of those accidents are serious enough to cause a standdown of the vehicle line, which interrupts the deployment of payloads. At the end of standdown, the vehicle resumes flying at a recovery flight rate (which is greater than nominal). The recovery flight rate continues until backlogged payloads have been flown and nominal flight rate operations are resumed.

If another accident and standdown occur during recovery operations, nominal flight operations may never be reached and the vehicle will always be flying at the recovery rate. To address this issue, resiliency is defined as the probability of failure during recovery operations. This can be expressed by a Poisson distribution of the form

$$Pf = 1 - e^{-(1-R)Nr} \tag{D.18}$$

where
- Pf = probability of failure during recovery period
- R = vehicle reliability
- Nr = number of flights during recovery period

The figure usually chosen for the required resiliency is Pf = .37 or about 1/e. This value results in at least a 50 percent chance of a successful recovery period with no failures.

In calculating Pf for a particular launch vehicle, the number of flights to be flown during its recovery period must be known. To determine this, assume a vehicle failure and standdown occurs. During the standdown, a backlog of flights result such that

$$Ro = (FR)(Td)(Bf) \tag{D.19}$$

where
- Ro = initial backlog of flights
- FR = nominal flight rate per month
- Td = standdown time in months
- Bf = backlog fraction

The backlog fraction represents the fraction of payloads scheduled to be flown during the standdown that remain at the end of the standdown. This assumes that as the standdown time gets longer, payloads disappear either by finding alternative launchers or by being cancelled. Assessing Bf is difficult, but it can be neglected by assuming it equals 1.0, i.e., that no payloads disappear. Some vehicles with unique capabilities may experience less balking than others for which substitutes are available. Bernstein and Abbott assumed a series of backlog fractions corresponding to various standdown times, as shown below.[21]

Standdown Time	Backlog Fraction
4 months	.94
6 months	.92
12 months	.83
18 months	.75

[21]Harry Bernstein and Dwight Abbott, "Space Transportation Architecture Resiliency," briefing, the Aerospace Corporation, El Segundo, CA, August 1987.

The initial backlog Ro is flown off at the recovery flight rate over a period of time X_1, shown as

$$Ro/FRr = X_1 \tag{D.20}$$

where FRr = flight rate during the recovery period

In the period of time X_1 taken to fly off the backlog, however, flights have been added to the backlog at the nominal flight rate. The new backlog is thus

$$(X_1)(FR) = R1 \tag{D.21}$$

This new backlog is flown off at the recovery flight rate such that

$$R1/FRr = X_2 \tag{D.22}$$

This process is continued until the X time values become negligibly small. The time values are summed to obtain the length of the recovery period.

$$(\Sigma X_i)(FRr) = Nr \tag{D.23}$$

Rather than calculating all the recovery time periods by hand, they can be expressed by an infinite geometric series which converges. Substituting Eq (D.19) into Eq. (D.20) results in

$$(Td)(Bf)(FR)/FRr = X_1 \tag{D.24}$$

The ratio of the recovery flight rate to the nominal flight rate is defined as the surge factor S, such that

$$FRr/FR = S \tag{D.25}$$

$$(Td)(Bf)/S = X_1 \tag{D.26}$$

This implies that $(X_1)/S = X_2$ (D.27)

Taking the constant terms outside the summation sign, the total recovery period is expressed as

$$\Sigma X_i = (Td)(Bf)\Sigma(1/S)^i \tag{D.28}$$

where i varies from 1 to n. The summation can now be expressed as a finite term so that

$$\Sigma X_i = (Td)(Bf)[(1/S)(1-(1/S)^i)/(1-(1/S))] \tag{D.29}$$

This assumes the surge factor is greater than 1. For the case of S = 1, the series does not converge, and the recovery period is undetermined. As n becomes large and the series converges, Eq. (D.29) reduces to

$$\Sigma Xi = (Td)(Bf)/S - 1 \tag{D.30}$$

Combining Eq. (D.30) with Eq. (D.23) and substituting into Eq. (D.18), the probability of failure becomes

$$Pf = 1 - e^{-(1-R)[(FRr)(Td)(Bf)/(S-1)]} \tag{D.31}$$

or alternatively, substituting in Eq. (D.25),

$$Pf = 1 - e^{-(1-R)[(FR)(Td)(Bf)(S)/(S-1)]} \tag{D.32}$$

From Eq. (D.32), a launch system's resiliency can be calculated given its reliability, nominal flight rate, surge factor, average standdown time, and the backlog factor for manifested payloads. Several implications for lowering Pf can be drawn from this equation. The probability of failure during recovery operations will drop as the surge rate and reliability increase, and as the standdown time, backlog factor, and nominal flight rate drop. The backlog factor can be lowered by making more payloads dual-compatible with other launch vehicles. The surge factor can be increased simply by operating the launch system well below capacity (which also lowers the nominal flight rate and the number of payloads manifested). This in turn implies other launch vehicles are available to launch space traffic.

D.6.3 Resiliency of Representative Architectures

Now that a resiliency measure can be calculated, how might resiliency considerations affect launch vehicle mixes? Assume a requirement to place about one million pounds of payload per year into LEO. This is about twice the amount launched in 1988, and is assumed to be composed of 50 percent DoD traffic, 40 percent NASA, and 10 percent commercial. A representative manifest to launch this amount consists of five launch vehicles, as shown below.

Representative Manifest I	
12 shuttle flights @ 50,000 lb	600,000 lb/year
8 Titan 4 flights @ 40,000 lb	320,000 lb/year
2 Titan 2 flights @ 5,000 lb	10,000 lb/year
4 MLV 1 flights @ 10,000 lb	40,000 lb/year
2 MLV 2 flights @ 15,000 lb	30,000 lb/year
Total	1,000,000 lb/year

This assumes no vehicles are bought for margin.

Given nominal flight rates in launches per year, and standdown times in months, *what are the resiliencies of the vehicles in this mix?*

Vehicle	FR	Td	Bf	R	Resiliency Goal of Pf ≤ .37 S = 1.25	S = 1.5
Shuttle	12	12	.83	.99	.39	N/A
Titan 4	8	6	.92	.95	.60	.42
Titan 2	2	6	.92	.92	.31	.20
MLV 1	4	4	.94	.96	.22	.14
MLV 2	2	4	.94	.95	.15	.09

Looking down the right-hand columns, the resiliency of the shuttle system is marginal with respect to the goal of .37. It would be acceptable if the flight rate could be surged by 50 percent, but that is not possible with current launch facilities and that option is labeled N/A. The Titan 4 system is particularly vulnerable to failure during recovery operations, indicating that its reliability should be raised or its nominal flight rate lowered. Off-loading payloads from the Titan 4 would involve increasing the flight rate of other ELVs (assuming payload compatibility), but the remaining ELVs have Pf numbers that could be allowably increased.

One way of lowering the number of shuttle and Titan flights without adding to the flight rate of the other ELVs would be to add a heavy-lift launch vehicle to the mix and redistribute the payloads. The Space Transportation Architecture Studies, among others, have recommended the creation of a vehicle capable of launching over 100,000 lb to LEO. Assuming a high reliability heavy-lift vehicle exists, payloads are redistributed as shown below.

Representative Manifest II	
4 heavy-lift flights @ 100,000 lb	400,000 lb/year
7 shuttle flights @ 50,000 lb	350,000 lb/year
4 Titan 4 flights @ 40,000 lb	160,000 lb/year
2 Titan 2 flights @ 5,000 lb	10,000 lb/year
5 MLV 1 flights @ 10,000 lb	50,000 lb/year
2 MLV 2 flights @ 15,000 lb	30,000 lb/year
Total	1,000,000 lb/year

This again assumes no vehicles are bought for margin.

The payload redistribution results in improvements to the resiliency numbers in this second architecture.

Vehicle	FR	Td	Bf	R	Resiliency Goal of Pf ≤ .37 S = 1.25	S = 1.5
HLV	4	12	.83	.98	.28	.18
Shuttle	7	12	.83	.99	.25	.16
Titan 4	4	6	.92	.95	.37	.24
Titan 2	2	6	.92	.92	.31	.20
MLV 1	5	4	.94	.96	.27	.17
MLV 2	2	4	.94	.95	.15	.09

Each of the launch vehicles now meets the resiliency requirement. An additional benefit from the addition of HLV flights is the ability to launch payloads previously too large or which had to be launched by the shuttle and assembled on-orbit.

D.6.4 Limitations of Resiliency Calculations

Resiliency is a useful framework for thinking about the factors affecting the successful operation of a space transportation architecture. It puts the individual vehicle reliabilities in a larger context with standdown times, planned flight rates, and needed recovery flight rates. It provides an understandable rationale for a mixed fleet of vehicles where standdowns occur independently of each other. This leads to a tradeoff between reliability and standdown time since the advantages of highly reliable systems can disappear if they experience long standdowns (as with the shuttle). Finally, by noting the importance of a recovery flight rate greater than the nominal flight rate, it underscores the importance of operating with some excess capacity.

Resiliency as developed here and by others has serious limitations in practice. Among the minor points are problems with calculating backlog fractions. Backlog behavior is difficult to predict a priori and may be virtually arbitrary. The effect is certainly real, but its magnitude is unknown. During standdown, it is assumed that payloads keep arriving for launch at the former, nominal, flight rate. Clearly, if payloads are evaporating due to balking at the backlog queue, payload owners will not keep sending their cargos to the launch site at pre-accident rates. Future efforts should look at linking balking behavior both during standdown and during recovery operations.

The concept of surging or having recovery flight rates above that of nominal rates is another problem. It is difficult to surge aircraft operations, much less launch operations, unless the fleets have substantial, preplanned, excess capacity. It is easy to imagine problems with surging shuttle flights, both technically and politically. Similar problems affect ELVs. The surge factor might instead be another way of saying that nominal flight rates will be kept below actual capacities. This assumes mission planners will resist pressures to pack in "just one more flight" to preserve an operating margin.

The distribution of a fixed demand over a larger number of vehicles certainly lowers the risk that many payloads will be caught by a single vehicle standdown, but at what cost? When payload costs are so much greater than launch costs, it is helpful to proliferate launch vehicles. On the other hand, making payloads dual-compatible (assuming it can be done) makes them more expensive and thus increases their already high costs. However, if space traffic demand increases greatly, some limit will eventually occur to the number of different vehicles the United States can field. The nation will run out of production facilities, launch control complexes, and even launch sites for additional new launch vehicles. Resiliency does not predict at what point this limit comes. At traffic levels where these limits are reached, Eq. (D.32) says only to emphasize reliability and short standdown times.

Resiliency concepts have not yet been extended to the use of cooperating launch systems. As shown earlier, if one system goes down and its payloads can be shifted to a compatible vehicle, the probability of meeting traffic demand rises quickly. It is a variant of the "excess capacity" strategy, but with more reasonable recovery flight rates. This can also limit the proliferation of launch vehicles at high demand levels and help control costs. Future efforts need to examine the effect of operational cooperation on the preferred mix of launch vehicles.

Finally, resiliency uses launch vehicle reliabilities as opposed to the reliability of the entire vehicle production and processing system. In the case of the shuttle, for example, there is a risk of losing an orbiter during carrier aircraft transport. ELVs can be affected by

accidents that shut down production facilities or limit the supply of crucial material.[22] The ALS program is addressing the larger problem of assuring industrial infrastructure support with an extensive industrial planning and modeling effort. Ideally, one would like to know the chance that the entire launch vehicle process will produce a successful mission, rather than just the reliability of the launch vehicle alone.

D.7 SUMMARY CONCLUSIONS

Two distinct but related topics have been covered in this appendix. The first was total cost per flight, and the other was the ability of a mix of vehicles to provide reliable access to space. The major cost observations were:

- Payloads are the predominant cost component in all flights, accounting for 75 to 90 percent of total per flight costs, depending on the specific mission.
- The risk exposure to payloads and launch vehicles of each flight is also a significant cost, accounting for an average of 4 to 8 percent of per flight costs.
- For a given level of risk exposure, heavy-lift launch vehicles need to have greater reliability than current ELVs—unless the cost of their payloads drops significantly.
- The combined average cost of payloads and launch vehicles strongly limits the amount of government space traffic that can be flown under current budgets (see Fig. D.16). The current cost line assumes payload costs of $35,000 per pound and launch costs of $3000 per pound. The potential cost line assumes costs of $10,000 per pound and $300 per pound, respectively.

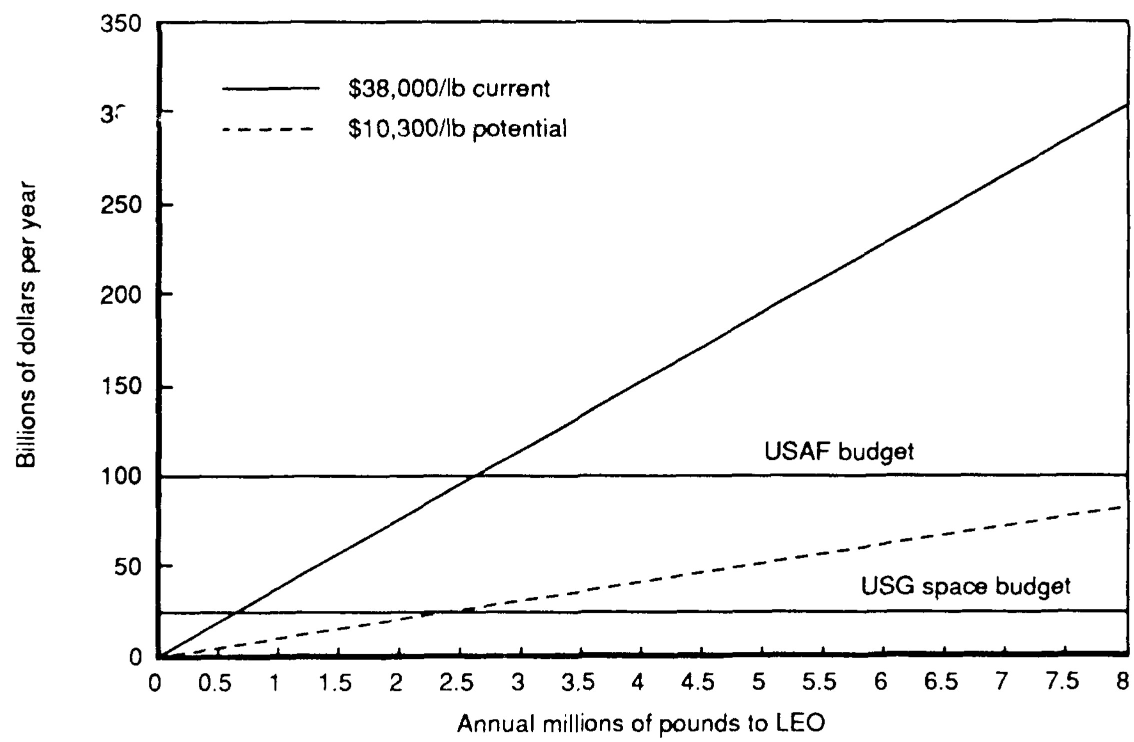


Fig. D.16—Total launch and payload costs and budgets

[22] "Government Heading Inquiry into Nation's Oxidizer Supply," *Aviation Week & Space Technology*, May 16, 1988, p. 19.

The major observations for reliable access to space were:

- There is a strong requirement for launch margin or "slack" in launch vehicle mixes to make up for accidents and standdowns. Acquiring margin by simply stockpiling additional launch vehicles quickly becomes very costly. An alternative is to hold nominal flight rates largely below full capacity to provide a "surge" capability after standdowns.
- Desirable goals for high reliabilities ($\geq$. 97) and short standdowns ($\leq$ 3 months) are significantly above historical experience. It is not clear that new systems will be able to improve on current figures without considerable operational experience.
- The probability of failure during a recovery period can be expressed as a Poisson distribution of the vehicle's reliability and the number of flights during the recovery period. The number of such flights is in turn a simple function of the nominal flight rate, the standdown time, surge rate, and the backlog factor. The latter term is an empirical expression of payload "balking" or cancellation while awaiting a flight during a standdown.
- Launch vehicle resiliency, defined as the probability of suffering a second failure while still recovering from an initial standdown, is a useful framework for thinking about operability issues. It provides a useful, if rough, metric that combines vehicle reliability, standdown times, and flight rates.

Resiliency does not incorporate options for dual-compatible payloads in its current state of development. Other work has indicated that cooperating backup vehicles and dual-compatible payloads are promising for assuring the on-time delivery of payloads. Further work needs to be done on the relative cost-effectiveness of this strategy relative to proliferating independent launch vehicles.

Appendix E
LAUNCH COSTS AND PAYLOAD COSTS

A major consideration for many space transportation planners is the effect of launch vehicles themselves on the payload market they serve. It is often argued that if access to space could be made cheap enough or convenient enough, then payload costs would drop as well. There is little historical evidence in space transportation for this effect, but is it also argued that necessary "breakthrough points" in launch costs have not yet been reached.

The following paper is a brief examination of the relation of launch costs to payload costs entitled, "Are Launch Vehicle Costs a Bottleneck to Economical Space Operations?" It was written by Carl H. Builder at The RAND Corporation in December 1969, about the time that the shuttle program was being considered as a more reliable, less costly means of space transportation that would also help control payload costs. The paper, originally an in-house draft, is included here to illustrate that many of the issues raised then are still part of space transportation debates. The author challenges much of the "conventional wisdom" expressed both then and now.

Are Launch Vehicle Costs a Bottleneck To Economical Space Operations?

INTRODUCTION

It is frequently hypothesized that the availability of a new low-cost launch vehicle would provide significant savings in space operations costs, over and above the direct cost savings associated with launch vehicles, because of the attendant effects upon payload costs and payload effectiveness. While the extent of these additional savings is implied to be great, it remains generally unquantified. The difficulties of assessing payload cost savings are certainly an obstacle to quantification, but the very existence of uncertainty in these savings can be used to advantage: Like buried treasure which has been located, but not seen or counted, the potential savings in payload costs can be proffered as an attractive bonus or expectation to tip the scales in favor of what might be an otherwise marginal proposal for a new low-cost launch vehicle. Under these circumstances, there is an incentive to find even indirect means for measuring the upper limits of the additional savings, as a first-order test of the hypothesis.

The following analysis is a simple attempt to bound the magnitude of payload cost savings which might accrue from the availability of a lower-cost launch vehicle. First, the conceptual notions which provide the basis for the analysis are developed and argued. Then the analytical relationships are introduced and an expression is derived for the minimum fractional cost of space operations with a new low-cost launch vehicle. The implications of this expression upon potential savings in payload costs are explored. Finally, the assumptions are critically reviewed as a means for exposing the limitations of the analysis.

CONCEPTS

There seems to be fairly wide acceptance of the notion that space launch costs are a bottleneck to the achievement of economical space operations. It is argued that the high cost of payloads is largely due to the high launch costs: We are forced to build very sophisticated, light-weight, highly reliable, and expensive payloads because the cost of transportation prohibits other approaches. If the transportation cost could be reduced, we could afford to launch heavier payloads or greater numbers of payloads. With heavier payloads, we could employ less sophisticated designs, making them less expensive, or we could build-in greater life or effectiveness, reducing the number of payloads and launches required. Alternatively, with larger numbers of payloads, we could afford to make them individually less reliable,

thus less sophisticated and less expensive, without sacrificing overall system effectiveness.*

If this logic is extended, an avenue of analysis is opened: Presumably, the above approaches to reducing space operations costs are presently denied only, or primarily, by launch costs. Any savings afforded by making the payloads less sophisticated, requiring them to be heavier or more of them to be launched, would be more than offset by increased transportation costs using present launch vehicles. If this is truly the case, then there is an implication that we find ourselves at some kind of economic saddle point for space operations costs using present launch vehicles: attempts to make payloads more or less sophisticated than they are at present will be unattractive because of payload costs on the one hand, or because of launch costs on the other. The concept of an economic saddle is consistent with the bottleneck theory, for one side of the saddle is supported by launch vehicle costs. If these costs can be reduced, one side of the saddle might be lowered, producing a long downslope to lower space operations costs.

For the purposes of this analysis, the concept of an economic saddle point with present launch vehicles and payloads is a valuable handle: It can be interpreted to mean that present payload designs represent a rational cost/effectiveness compromise in the light of present launch vehicle costs.

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*Still another proposed approach to payload cost savings is the recovery and reuse of payloads by means of a recoverable launch vehicle. Certainly a recoverable launch vehicle is one possible approach to a low-cost launch vehicle, but the bottleneck hypothesis is most frequently associated with the high cost of present space transportation and is not generally restricted to the issue of payload recovery. Since low-cost expendable launch vehicles have been proposed as a means for breaking the bottleneck, and since recoverable launch vehicles are a special case within the class of low-cost launch vehicles, this analysis treats the general case: where the new launch vehicle simply reduces the space transportation costs.

In effect, this interpretation leads to an assumption that present payloads are optimally sized for present launch vehicles. While the validity of this assumption is certainly not demonstrable, it can be supported by the antithesis: If present payloads are not optimally sized for present launch vehicles, any potential cost savings presently unrealized, because of this, should not be credited to a new low-cost launch vehicle. Or put another way: the validity of the bottleneck hypothesis or the economic justification for a new launch vehicle should not and cannot depend upon the assumption that we have failed to take advantage of cost savings now available to us within the characteristics of present payloads and launch vehicles, and that we will somehow overcome this failure if a new launch vehicle is made available.

If current payload designs are assumed to represent an optimum tradeoff for the cost/effectiveness of space operations using current launch vehicles, the nature of present (and possibly future) payload design tradeoffs can be analytically deduced, at least to the extent of defining the maximum cost savings from payloads designed to take advantage of a new low-cost launch vehicle. This deduction and its implications are at the center of the analytical approach used here.

ANALYSIS

First, consider the set of space operations which might alternatively be conducted with present launch vehicles or a new low-cost launch vehicle. The payloads, if designed for present launch vehicles, would require a certain number of launches, N. Assuming that the payloads would have some average cost, C_p, and that the present launch vehicles required have some average cost,

C_v, the total cost to conduct this set of space operations would be:

$$C_t = N\,(C_p + C_v) \tag{1}$$

Suppose that the average weight of these payloads was increased from W to V in order to realize payload cost savings, albeit at the expense of increased launch costs. This increase in payload weight might be used to make the payloads cheaper or to increase their effectiveness (as by increasing payload life), or both at the same time. The most obvious effect of increasing the payload weights would be to increase the launch costs, if we are constrained to use the present inventory of launch vehicles. Even a cursory examination of present launch vehicles will show that the costs are reasonably represented by an exponential function of payload capacity. Thus, if the average payload weight is increased from W to V, we should expect that the average launch vehicle cost will increase from C_v to:

$$C_v \left(\frac{V}{W} \right)^{\beta}$$

where β is the scaling exponent for present launch costs with payload weight capacity.

Less obvious are the effects of increased payload weight on payload cost and effectiveness. Suppose, however, that payload cost goes down and payload effectiveness goes up, both exponentially, as payload weight is increased. While this may not be true, the exponential formulation frequently applies to these types of tradeoffs and can be made to approximate a great variety of relationships if the value of the exponent is not constrained. If payload costs do scale up or down exponentially with weight, then as the payload weight is

increased from W to V, the average payload cost will go from C_p to:

$$C_p \left(\frac{V}{W} \right)^{\gamma}$$

where γ is the scaling exponent for payload cost with payload weight. γ will be negative if costs go down with increasing weight.

Alternatively or simultaneously, the increase in payload weight could be used to increase payload effectiveness. Since we are concerned here with the cost of a set of space operations, having some total measure of effectiveness, any increase in individual payload effectiveness must be manifested in cost savings. If the increase in payload weight permits one payload to do the work of several, as by increased life or functions, then this increased effectiveness can be directly related to the required number of launches. If payload effectiveness does scale exponentially with payload weight, then as the payload weight is increased from W to V, the required number of launches will go from N to:

$$N \left(\frac{W}{V} \right)^{\delta}$$

where δ is the scaling exponent for payload effectiveness with payload weight. δ will be positive if effectiveness goes up with weight.

Combining these effects, if the payload weight is increased from W to V, and we continue to use launch vehicles from the present inventory, the total cost of the set of space operations becomes:

$$C_t = N \left(\frac{W}{V} \right)^{\delta} \left[C_p \left(\frac{V}{W} \right)^{\gamma} + C_v \left(\frac{V}{W} \right)^{\beta} \right] \qquad (2)$$

If there is an optimum average payload weight, V, for minimum space operations costs, it can be found by differentiating Equation (2) with respect to V and setting

the result equal to zero. Solving the resulting expression for V gives:

$$V_{opt} = W \left(\frac{C_p}{C_v} \quad \frac{\delta - \gamma}{\beta - \delta} \right)^{\frac{1}{\beta - \gamma}} \tag{3}$$

If, as discussed earlier, present payloads are rationally sized in the light of present launch vehicle costs, then, at least approximately, we should expect that:

$$V_{opt} = W \tag{4}$$

The only justification for this not being true would be the discrete characteristics of the present launch vehicle inventory: the optimum payload size might fall somewhere in between the capacities of two current launch vehicles, and there would be a tendency to design the payload exactly to the capacity of one or the other. But the inventory of present launch vehicles is large enough to warrant approximation as a continuum of vehicles and justify Equation (4).

Equation (4) permits solution of Equation (3) for any one of the scaling exponents in terms of the others. For example:

$$\gamma = \delta + \frac{C_v}{C_p} \left(\delta - \beta \right) \tag{5}$$

The significance of Equation (5) is that payload cost or effectiveness tradeoffs with payload weight are not unbounded or unrelated to each other or to the tradeoffs in launch vehicle capacity and cost. If unlimited improvements in payload effectiveness and cost could be achieved by simply making the payloads larger, we would be moving all of our payloads to the largest launch vehicle available (e.g., the Saturn V). If our present design of payloads and their assignment to launch vehicles is anywhere near rational, there must be some

limits on how fast payload cost and effectiveness improve with payload weight, and these limits depend upon how fast the costs of present launch vehicles rise with payload capacity. Equation (5) is an expression of these limits.

Now suppose that a new low-cost launch vehicle becomes available, and that the average launch cost is reduced to some fraction, f, of that for present launch vehicles, regardless of size. This may overstate the case for most new launch vehicle proposals, where the cost savings are usually defined only for maximum payload capacity, but we might argue that a new launch vehicle concept is a new transportation technology which applies to any size launch vehicle. In any event, since this analysis deals in limits, it will not harm to define f for the most favorable payload size and then apply it to all sizes. This is not to ignore the very real problem of properly sizing a new low-cost launch vehicle, but to defer the question in favor of finding an upper limit for payload cost savings attendant to any cost reduction for launch vehicles.

If the payloads are not resized to take advantage of the new low-cost launch vehicle, the total cost of the set of space operations is simply:

$$C_t = N\left(C_p + f\,C_v\right) \tag{1a}$$

But if the payloads can be resized, from W to V, then:

$$C_t = N\left(\frac{W}{V}\right)^{\delta}\left[C_p\left(\frac{V}{W}\right)^{\gamma} + f\,C_v\left(\frac{V}{W}\right)^{\beta}\right] \tag{2a}$$

Equation (5) can be used to eliminate one of the three scaling factors:

$$C_t = N\left[C_p\left(\frac{V}{W}\right)^{-\frac{C_v}{C_p}(\beta-\delta)} + f\,C_v\left(\frac{V}{W}\right)^{\beta-\delta}\right] \tag{6}$$

To find the optimum payload size, Equation (6) may be differentiated with respect to V and the resulting expression set equal to zero. Solving for V gives:

$$V_{opt} = W\, f^{\frac{1}{\left(\frac{C_v}{C_p} + 1\right)\left(\delta - \beta\right)}} \qquad (7)$$

Assuming that the payloads will, in fact, be resized optimally for the new low-cost launch vehicle, Equation (7) may be substituted in Equation (6) to give the minimum cost of the set of space operations:

$$C_t = N \left(C_p + C_v \right) f^{\frac{\frac{C_v}{C_p}}{\frac{C_v}{C_p} + 1}} \qquad (8)$$

Comparison of Equations (1) and (8) shows that the fractional cost of the set of space operations with the new low-cost launch vehicle, as compared to the same costs with present launch vehicles, when the payloads are optimally sized for minimum total cost in both cases, is simply:

$$F = f^{\frac{\frac{C_v}{C_p}}{\frac{C_v}{C_p} + 1}} \qquad (9)$$

Since the ratio of present launch vehicle costs to payload costs is always a positive number, the exponent in Equation (9) is always fractional. Thus, the total cost of the set of space operations will never reduce at a faster rate than the cost of launch vehicles, even if the payloads are redesigned to take advantage of the lower launch vehicle costs. This, in turn, means that the payload costs will always reduce more slowly than the costs of launch vehicles, so long as the payload

cost reductions are simply a response to launch vehicle cost reductions. Thus, there is no "snowball" effect.

If, as a rough approximation, present payloads cost as much as their launch vehicles, the exponent in Equation (9) becomes one-half; and space operations costs will vary as the square-root of launch vehicle costs. A four-fold reduction in launch vehicle costs could, at most, produce a two-fold reduction in the total cost of the space operations involved. While a 50-percent reduction in total costs is certainly significant, a little arithmetic will show that three-fourths of these savings are derived directly from launch vehicle cost savings, while only one-fourth of the total cost savings could be attributed to redesign of the payloads.

Again, if present payloads cost about as much as their launch vehicles, then a ten-fold reduction in launch vehicle costs would result in a maximum of about a three-fold reduction in the space operations costs. About two-thirds of these total savings would come from the launch vehicles, while the other third would come from the payloads. Thus, while not denying the existence of possible payload cost savings attendant to the availability of a new low-cost launch vehicle, the analysis does indicate that these payload savings are not likely to be a dominant factor in the economic arguments. This observation is the essence of the analysis.

The ratio of present launch vehicle to payload costs does have some effect upon the relative magnitude of the potential payload savings attendant to reduced launch vehicle costs. The lower the ratio, C_v/C_p, the greater the relative payload savings, but this is mainly because the launch vehicle savings and the total savings are smaller. In other words, to find conditions where the payload savings are relatively large, we must resort to cases where the total cost savings are relatively small, and therefore less interesting. Conversely, if we look for conditions where the total cost savings are large, we find that the payload savings are a relatively small part of the total. Thus, the observation that

payload costs are not dominated by launch vehicle costs depends upon the form of the analysis, and not upon the assumption of numerical values for the variables.

DISCUSSION

The preceding analysis, while probably not trite, is so simple and glib that instead of being disarming it may evoke suspicions of treachery. The implications of the analysis are clear enough that they do not need any further discussion; but they are also so confining and, perhaps, contrary to popular notions or intuitions, that the challenges to the analysis ought to be discussed.

The arithmetic is too easily checked; it is the assumptions which warrant scrutiny. Fortunately, the assumptions are few in number.

Assumption 1. Space operations costs can be characterized by average unit costs for launch vehicles and payloads, summed over the number of required launches.

Current space operations are characterized by great diversity in launch vehicles and payloads, and the notion of average costs for these elements is somewhat analogous to specifying an average size for rocks. But this difficulty can hardly be used to challenge the validity of the analysis. For example, the set of space operations under consideration could be narrowed to the single class of payloads which best display the advantages of a new low-cost launch vehicle. Average unit costs for payloads and launch vehicles can certainly be determined for this narrow set of space operations, and the broad implications of the analysis should remain unchanged.

Assumption 2. The unit costs for present launch vehicles vary exponentially with payload weight capacity.

No problem here. While there might be some argument as to the value of the exponent, no specific value is required in the analysis.

Assumption 3. A new low-cost launch vehicle will cost some constant fraction of present launch vehicles at the same payload capacity.

This assumption, while it simplifies the analysis, raises some issues worthy of discussion. First, there is no obvious reason why new launch vehicle costs should vary exponentially (and particularly with the same exponent) as present launch vehicles with respect to design payload capacity. It may well be argued that the costs of some new launch vehicle concepts should be considerably less sensitive than present launch vehicles to design payload capacity. However, this objection can be overcome if f is defined as the minimum value attainable when a new low-cost launch vehicle is compared with any of the present launch vehicles that would be forced to compete on the basis of payload capacity. This approach overstates the cost savings of the new launch vehicle, but that is in keeping with the nature of an analysis to define limits.

But another, more subtle difficulty arises from the probability that a new low-cost launch vehicle will compete economically with several vehicles from the present inventory. If payloads are shifted from the smaller of the present vehicles, the new launch vehicle will offer considerable excess payload capacity, and the criteria for payload design optimization will differ from that used in this analysis. Instead of trading-off launch vehicle cost for payload cost, the cost of the launch vehicle will be essentially constant with payload size, up to the maximum payload capacity of the new vehicle. Thus, there should be far greater incentive to increase payload weights to reduce their cost or improve their effectiveness. To some degree, therefore, the analysis underestimates these potential payload savings. But under the same conditions, the analysis overestimates the launch vehicle savings, and a little reflection upon the nature of the analytical relationships will reveal that the total cost savings are also overestimated. Thus, Equation (9) remains valid as a limit for the

total cost reductions afforded by a new low-cost launch vehicle, but the apportionment of savings between payloads and launch vehicles is undetermined.

<u>Assumption 4</u>. Payload cost and effectiveness vary exponentially with payload weight.

The obvious challenge to this assumption is the speculation that the functions might be discontinuous. This challenge is appealing, for it would support the notion that we now find ourselves in some kind of economic saddle region; and, given a significant enough reduction in launch costs, we could greatly reduce the payload costs. The concept of step-functions in payload cost and effectiveness is also compatible with the notion that entirely new approaches and philosophies of payload design would appear w[illegible]wer transportation costs.

As an example, assume that a particular payload costs as much as its present launch vehicle, and that present launch vehicle cost is proportional to payload capacity. A two-fold increase in the payload weight would, therefore, wipe out any possible saving in payload costs because of the increase in launch vehicle costs. Thus, if the payload costs were somehow subject to dramatic reductions when the payload weights were increased more than two-fold, the present launch vehicle inventory would deny any opportunity to take advantage of these payload cost savings, even if the payload costs went to zero. But a new low-cost launch vehicle could take advantage of such a price break. A new launch vehicle costing one-tenth of present vehicles could capitalize upon favorable cost discontinuities occurring out to twenty-fold increases in payload weight.

The validity of the analysis is, therefore, limited to continuous (or approximately so) relationships between cost or effectiveness and payload weight. In effect, the analysis presumes that the economic and design forces which determine today's payloads will continue to be operative, in direction if not degree, when lower-cost

launch vehicles become available. Certainly, this presumption can be challenged.

But, if the limits on cost savings defined by this analysis are to be exceeded by means of the counter-presumption (i.e., the functions are discontinuous), then we should be obliged to pose a mechanism for the discontinuities. Are there design approaches to payloads that could decrease costs or increase effectiveness, at the expense of weight, which cannot be implemented piece-meal or by degrees? Moreover, it is not enough to show that certain changes would have to be made on an "all-or-nothing" basis (e.g., changes in power supplies), the changes must have a significant impact upon payload cost or effectiveness, or many smaller changes must somehow be linked together to force the discontinuity.*

These considerations imply that payload cost savings by evolutionary improvements, afforded by the availability of a new low-cost launch vehicle, are constrained as described by this analysis. But payload cost savings by revolutionary improvements, perforce involving large and discontinuous changes in cost or effectiveness, may lie outside the limits circumscribed by this analysis.

Assumption 5. Payload designs are and will be optimized for the minimum total cost of a set of space operations having some overall measure of effectiveness.

The concept that present payloads are optimally designed for their launch vehicles, and that future payloads will be optimized for any new low-cost launch vehicle, was discussed in detail at the outset. Even if not a valid assumption, the concept is useful as an accounting convention.

However, the criteria of minimum cost and fixed effectiveness for a set of space operations may be

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*An obvious possibility for discontinuous trends in payload cost and effectiveness would be payload recovery and reuse. Payload recovery is an "all-or-nothing" measure which could have a pervasive effect upon payload designs.

criticized as follows: The real objective of a new low-cost launch vehicle is not to reduce the expenditures on space operations, but to increase the effectiveness of space operations with the money we are now spending. Savings on launch vehicles and payloads can be used to expand space operations and increase their effectiveness. With an expanded level of operations, there will be further savings because of operations scaling effects (e.g., learning effects).

Operations scaling effects are not included in the analysis because they do not appear to be central to the issue under examination: the effect of launch vehicle costs upon payload costs. In the absence of operations scaling effects, the analysis remains valid even if cost and effectiveness are interchanged for the objective variable and constraint. The cost reductions can simply be inverted to find the effectiveness increases.

What emerges from this review of the assumptions is a clearer distinction of the application and limitation of the analysis. If payload savings are to be a significant aspect of reducing the cost of future space operations, they will have to be more than the simple consequence of lower launch costs. If payload costs and effectiveness evolve in a continuous and evolutionary manner from tradeoff opportunities now existing, the payload cost savings attendant to the availability of a new low-cost launch vehicle will not be large as compared to the direct savings on launch costs. To escape this conclusion, we shall be forced to seek revolutionary and pervasive design approaches which will have significant and discontinuous effects upon payload cost and effectiveness. Payload recovery and reuse is one possibility. If we are confident enough to predict the cost savings for a recoverable launch vehicle, we ought to have the audacity to assess the cost savings from recovering and reusing payloads as well. The realities are that we are

not yet certain of our abilities to estimate the savings in either case.

The analysis presented here does not seem to support the theory that launch vehicle costs are a bottleneck to significantly lower payload costs. While significant reductions in payload cost may be possible, they appear to depend upon factors other than the cost of launch vehicles alone; and to assume that these factors will be favorable with the advent of lower transportation costs remains largely a matter of faith.

Appendix F
SURVEY QUESTIONNAIRES

Evaluation Criteria for U.S. Launch Vehicle Planning 1990-2010

November 1988

This survey is being conducted as part of a doctoral dissertation at the RAND Graduate School. Individual responses will be treated as anonymous. The results will be aggregated by the respondent's top-level organization (e.g., Executive Branch, Congress, NASA, the Air Force) and combined with other analyses of U.S. launch vehicle options. Copies of the final report survey results will be provided to each respondent.

1. **Selecting Evaluation Criteria for Launch Vehicle Mixes**

There are many possible criteria that might be used to evaluate the desirability of a specific mix of launch vehicles. What criteria do you believe to be the most important for your organization?

Please rank order each group of criteria listed below (with 1= most important) For example, within the Cost group, rank the listed criteria from 1 to 8. Feel free to add additional criteria and ignore those criteria that are not relevant to senior decision-makers.

A. Cost of the Launch Vehicle Mix

1. Min. non-recurring costs
   (e.g., DDT&E, facilities, reusable elements)
2. Min. recurring costs
   (e.g., O&S, expendable elements, unreliability costs)
3. Min. life-cycle cost, undiscounted
4. Min. life-cycle cost, 5% discount rate
5. Min. life-cycle cost, 10% discount rate
6. Min. life-cycle cost sensitivity to demand levels
7. Min. total annual budget growth rate
8. Min. peak annual funding requirement
9. Min. total payload costs
10. Other:

B. Performance Characteristics of the Launch Vehicle Mix

1. Max. payload capacity consistent with demand
2. Max. operational availability
3. Max. compatibility with the Space Transportation System
4. Min. compatibility with the Space Transportation System
5. Max. survivability through crises level of conflict
6. Max. security for sensitive equipment and information
7. Max. flexibility in handling upper stages
8. Max. flexibility for future performance upgrades
9. Max. services to payloads
10. Min. services to payloads
11. Others:

C. Programmatic Risk of the Launch Vehicle Mix

1. Min. non-recurring cost risk in development
2. Min. recurring cost risk in operations
3. Min. life-cycle cost risk of the launch vehicle mix
4. Min. technical risk of the launch vehicle mix
5. Max. availability of industrial infrastructure
6. Max. ability to change capabilities during development
7. Min. schedule risk in development
   (e.g., change in estimated year of full operational capability)
8. Others:

D. Operational Risk of the Launch Vehicle Mix

1. Max. environmental acceptability
2. Max. safety for involved personnel
3. Max. safety for third-parties
4. Max. probability of an intact abort
5. Max. reliability of launch vehicles
6. Min. vehicle standdown time after an accident
7. Max. ability to surge flight rate after an accident
8. Max. availability of alternate vehicles for payloads
9. Others:

For the next two groups, please rank order the issues listed by their importance to your organization.

E. Mission Implications of the Launch Vehicle Mix

1. Provide a heavy-lift capability (100,000 lbs.+ to LEO)
2. Supports Space Station deployment
3. Supports Space Station operations
4. Supports new civil space initiatives (e.g., Mission to Earth, Lunar Base, Manned Mars)
5. Supports SDI missions
6. Supports new non-SDI military missions
7. Continues/expands U.S. manned spaceflights
8. Lowers/eliminates U.S. manned spaceflights
9. Provide incentives for smaller, more numerous payloads
10. Others:

F. Policy Implications of the Launch Vehicle Mix

1. Perception of U.S. leadership in space transportation
2. Level of U.S. public support
3. Potential Soviet responses
4. Potential Allied responses
5. Opportunities for new technology R&D
6. Support for U.S. commercial ELV industry
7. Relative responsibilities of the individual armed services for peacetime launches
8. Relative roles of DoD and NASA in peacetime launches
9. Relative size of DoD and NASA space budgets
10. Geographical distribution of contracts
11. Relative roles of NASA HQ and field centers
12. Future of the Space Transportation System
13. Future of manned space flight
14. Others.

2. **Selecting Relative Weights for the Evaluation Criteria**

Some evaluation criteria are likely to be more important than others. Some criteria may constitute hard constraints or requirements for an acceptable launch vehicle mix.

Please weight the criteria groups by their relative importance (i.e., all weights add to 100%) and indicate whether any specific criterion ranked above is a requirement. Neglect criterion that are weighted less than 1%. Categories may also be combined if you wish (e.g., combining policy and mission implications).

Percent Weight

Cost of the Launch Vehicle Mix--------------------------

Policy Implications of the Launch Vehicle Mix---------

Mission Implications of the Launch Vehicle Mix-------

Operational Risk of the Launch Vehicle Mix------------

Programmatic Risk of the Launch Vehicle Mix---------

Performance Characteristics of the Mix----------------

Total = 100%

Specific criteria which are requirements for your organization:

1.

2.

3.

4.

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Alternative Traffic Demand Levels and Launch Vehicle Mixes for the United States 1990-2010

November 1988

This survey is being conducted as part of a doctoral dissertation at the RAND Graduate School. Individual responses will be treated as anonymous. The results will be aggregated by the respondent's top-level organization (e.g., Executive Branch, Congress, NASA, the Air Force) and combined with other analyses of U.S. launch vehicle options. Copies of the final report survey results will be provided to each respondent.

1. **Key Issues in Selecting Launch Vehicle Mixes**

What key issues affect (or will affect) the selection of launch vehicle mixes by the U.S.? How do you believe these issues will *change (if at all) in the future?*

Issues in the Next 1-4 Years (1989-1992):

Issues in the Next 5-10 Years (1993-2000):

Issues in the Next 10-20 Years (2000-2010):

2. **Ranking Alternative Estimates of Future Space Traffic Demand**

The choice of launch vehicle mix depends, of course, on the expected levels of traffic. Current DoD and NASA manifests extend to about 1995. Major alternatives beyond 1995 could be:

1. Nominal Demand - as defined by the Space Transportation Architecture Study (STAS Level 2/II) or the Advanced Launch System normal demand. The STAS levels would be about 20-30 equivalent Shuttle flights per year. The ALS level would increase steadily to about 60 equivalent Shuttle flights in 2010.

2. SDI Deployments - as defined by the STAS models or the ALS expanded demand. The demand levels for both models would increase to 120-140 equivalent Shuttle flights by 2010.

3. Expanded Civil Space Program - new civil efforts such as manned missions to Mars or a manned lunar base could increase demand to peaks of 35-70 equivalent Shuttle flights as defined by STAS.

4. Constrained Demand - if space spending is reduced and new starts are cancelled, demand may fall to 10-15 equivalent Shuttle flights per year. This would mean a cancellation of the Space Station program and no new starts for the DoD.

Questions:

1. What are your estimates of the probability of occurrence for each of these traffic demand levels? (Probabilities do not have to sum to 100%). Also, how would you rank the above traffic demand levels in order of likelihood (most likely to least likely)?

	Probability of Occurrence (0%-100%)	Likelihood Rank (1-4)
Nominal Demand-----------		
SDI Deployments-----------		
Expanded Civil Space-------		
Constrained Demand--------		

2. What levels of traffic demand would you see as desirable for the same time period? What levels of traffic demand would you see as least desirable?

Most desirable:

Least Desirable:

Ranking Alternative Estimates of Future Space Traffic Demand (cont.)

3. What are the major <u>uncertainties</u> (if any) in determining space traffic demand levels? (e.g., national policies, launch vehicle choices, changing payload designs, available budgets)

3. **Ranking Alternative Mixes of U.S. Launch Vehicles**

The U.S. is facing a variety of options for launch vehicles during the next two decades. In addition to existing vehicles such as the Shuttle and Titan, there are proposed vehicles such as the Shuttle-C and the ALS family of vehicles. New vehicles may be introduced from the private sector (e.g., Delta 2s and Atlas 2s) or from technological breakthroughs (e.g., the National Aerospace Plane program).

How would you **rank the desirability** (e.g., most desirable=1) of the launch vehicle mixes listed below **for each level** of demand? Feel free to add other combinations that you would see as more desirable for each demand level.

1. Constrained Demand
   - a. All ELVs after 1995
   - b. All STS after 1995
   - c. A reduced level mix of STS and ELVs
   - Other:

2. Nominal Demand
   a. Continue current STS/ELV levels
   b. plus Shuttle-C
   c. or plus additional ELVs
   Other:

3. Expanded Civil Demand
   Continue STS and ELV levels
   a. and add ALS vehicles
   b. or add ALS and Shuttle-C vehicles
   Other:

4. Expanded DoD Demand
   Continue STS and ELV levels
   a. and add ALS vehicles
   b. or add ALS and Shuttle-C vehicles
   Other:

5. What mix of launch vehicles would you choose given <u>uncertainty</u> as to the actual demand level? What decisions can or should be delayed until the demand level became clearer?

Appendix G
POLITICAL FACTORS AFFECTING SPACE TRANSPORTATION PLANNING

This appendix will illustrate many of the pitfalls, biases, and problems that can occur in space transportation planning. Readers familiar with these issues should be among the more informed consumers of space transportation analyses. The problems themselves are not so much failures of technique as they are examples of the influences created by political and institutional factors. The experienced space transportation planner and decisionmaker is usually well acquainted with the examples presented here.

As an illustration of the need for space transportation planning, take the case of congressional desire for "an overall Space Recovery Program reconciling the separate DoD and NASA programs to meet the nation's present and future (FY 2000) space launch requirements."[1] How might political factors affect the conduct of a study to produce such a program? Answering this question requires examining the progression of a study from its commissioning, the conduct of analyses, and the use of the findings.

The first and most important question is to ask what kind of analysis is needed. There are three general approaches to analyses: assess a current program, design a new program to solve a problem, or determine what the problem is or might be. The development of an overall Space Recovery Program will likely require a combination of all three approaches. Forecasts are made of future traffic demand to determine potential shortfalls or overcapacities. New launch vehicles are designed to redress real or perceived deficiencies with current vehicles. Launch schedule slippages, loss rates, and costs are assessed to see how well current vehicles function.

G.1 COMMISSIONING THE STUDY

Who should be commissioned to create a Space Recovery Program plan? Congress has asked the President to supply a plan, but he has latitude in whom he designates to lead the study, providing he wishes to respond at all. Such studies can risk constricting future political options. The study could be done by the OMB, or as a joint task between the Department of Defense and NASA, with or without external contractors from industry. Alternatively. the Congress could ask for a study from its own resources, such as committee staff, the Congressional Budget Office, or the Office of Technology Assessment.[2]

The primary issues that will color the study are budgetary struggles between the White House and the Congress, and the differing priorities of NASA and the Department of Defense. Both of these are largely driven by conflicts over the relative turfs organizations. The Congress will desire lower budget requests, not only for the Department of Defense, but for NASA as well.[3] The Department of Defense will want to press ahead with the ALS program unless it sees inevitable tradeoffs with more valuable programs. The NASA will voice support for the ALS technology effort, but will concentrate its resources around the troubled space station program. Any budgetary wedge available for space transportation development would, in NASA's view, be best spent for a Shuttle-C.

[1]"DoD, NASA Space Plans Questioned by Senate Appropriations," *Aerospace Daily*, December 10, 1987, p. 369.

[2]For example, a study on "Manned Space Transportation Architectures" was released by the Office of Technology Assessment in August 1989.

[3]"Interdependence of NASA Programs Puts Congress in Budget Bind," *Aviation Week and Space Technology*, May, 16, 1988, p. 21.

Space issues have been largely bipartisan to date. So far, partisan politics seem to stop at the atmosphere, if not at the water's edge. This argues, of course, that debates over SDI are not really space issues, but terrestrial military ones. If the interim ALS had not been withdrawn, or if an SDI deployment becomes reality, then partisanship can be expected as space transportation is brought into the larger debate over military policy. Barring SDI deployment however, a Space Recovery Program plan could expect bipartisan support and criticism.

The functional groups immediately affected by a space transportation study would be those industries building and operating ELVs, shuttles, and developing new systems under study contracts. Indirectly, the users of deployed space systems would also be affected. These groups are rather wide and diffuse. They include users of military satellites, commercial communications satellites, weather satellites, scientific probes, and new orbital facilities such as the space station. These groups are primarily interested in low cost, reliable access to space, and are unlikely to become an organized interest group unless a major interruption in space access appears. They are interested in the study proceedings in order to plan their own programs efficiently.

Although both NASA and the Department of Defense have their own priorities for space transportation, NASA has tended to see space flight as more of an end in itself than the Department of Defense. Cutting across all the players in space transportation are three major schools of thought on the utility of space.[4] In brief, the first school sees space as fundamentally unexploitable or undependable, good only for science, political exhibitions, and noncritical military tasks (such as weather predictions during peacetime). The second school sees space as useful on a case-by-case basis, as with communications, weather, and surveillance satellites. It is the particular mission itself which is important, and space is simply one arena of operations to meet needs on Earth. The third school sees space as fundamentally crucial to humanity's future. This school professes a faith that space will be an important theater of military operations in its own right, as well as a place for human industry and settlements.[5]

Commissioning a study from an organization or persons who see space development as a mission in its own right (e.g., the third school above) risks biasing the study in favor of the most technically ambitious space transportation plans. In contrast, using the OMB or CBO risks giving greater weight to expected budgetary limits and less regard to other national interests. A joint NASA/DoD study could represent the widest range of views, but would be unlikely to consider budgetary limits as low as those by CBO and OMB. In any event, the use of contractors is unlikely to be helpful except in adding technical depth to alternatives "allowed" by the government client hiring them.

Commissioning industrial contractors to study launch vehicle planning can create several types of biases. The government sponsor, whether NASA or Department of Defense, may try to cover the entire set of credible industrial contractors with study contracts. This increases competition, attracts matching company funds in a demonstration of their support of the (usually underfunded) study, and encourages contractor political support for desired hardware contracts in Congress. A simple example of the latter tactic would be to divide up proposed work to include contractors in important congressional districts, key military bases, or research centers.

Limited amounts of national technical talent and budgets, however, mean that pursuing one program creates opportunity costs for other efforts. These opportunity costs may be borne by more than one sponsor. For example, if technical talent for space vehicles is tied up on one program, competing sponsors may not be able to gain entry to that talent for their programs. Like other valued resources, launch vehicles can be fought over as part of an

[4]Dana J.Johnson, "The Evolution of Military Space Doctrine," Ph.D. dissertation, University of Southern California, Los Angeles, 1987.

[5]National Commission on Space, *Pioneering the Space Frontier*, Bantam Books, New York, May 1986.

organization's turf, with "owning" preferable to sharing (as in the DoD usage of the shuttle) for a variety of functional and institutional reasons.

In summary, the Congress would like a comprehensive study of space transportation systems that supports budgetary planning and identifies political tradeoffs. The Congress would also like the study done as soon as possible. The President is reluctant to initiate such a study as it may limit future maneuvering room and require confronting painful tradeoffs between the Department of Defense and NASA. A comprehensive analysis, such as done under the STAS studies, risks being overtaken by events such as the Challenger accident. Shorter studies for immediate budgetary needs risk being shallow and driven by current events rather than by a longer-range sense of where the country should be headed. Finally, a joint NASA/DoD effort includes the major players, but lacks direct fiscal responsibilities that are crucial to implementing study recommendations.

G.2 CONDUCTING ANALYSES

The study may be conducted by persons or organizations with particular biases, such as those desiring a larger (or smaller) budget for space transportation, a greater (or lesser) role for the Department of Defense in space transportation, or a larger (or smaller) role for manned spacecraft. How might the study be influenced to appear dispassionate on the surface, yet come up with the "right" answers? Or even if the study is performed with the most objective of intentions, what influences might occur due to its institutional setting (say, within the OMB, DoD, or NASA)? Answering these questions requires going into a considerable level of detail.

No matter the source, space transportation plans often contain multiple "hidden agendas" that reflect the objectives of the sponsoring organizations. An awareness of these agendas is important to interpreting the results of analyses, as is shown below.

G.2.1 Hidden Agendas

In addition to general statements of policy or mission, institutions like to have visible signs of their purpose.[6] The Strategic Air Command has bombers and tankers, the Tactical Air Command has fighters, and it is natural that the USAF Space Command would want its own launch vehicles, such as the ALS. Launch vehicles can also support other visible signs—the Shuttle-C could support the space station that NASA wants. Studies which question the value of the systems per se or propose major alternatives are unlikely to be well received by a sponsor institutionally committed to such tangibles.

Aside from the creation of new vehicles, a space transportation plan may nonetheless recommend advancing launch vehicle technologies or making do with current systems. In addition to technical and budgetary issues, the study may reflect a sponsor's agenda to emphasize the development of new technologies versus pursuing a major hardware contract. The latter is more lucrative, the former easier to accomplish.

A sponsor or a contractor may decide to emphasize certain technologies as part of a larger strategic plan to position itself for future hardware contracts when a budgetary opening occurs. The issue of who will develop new propulsion systems, NASA or the Air Force, is but one example and often is a precursor to broader vehicle development decisions. Thus, debates over research turf are not limited to scientific priorities, but also reflect competition for major new programs.

In any event, how might space transportation planning be "gamed"? Space transportation planning requires forecasts of the future in several areas which are vulnerable to bias. Forecasts are required for future space traffic demand, alternative launch vehicles,

[6]Carl H. Builder, *The Masks of War*, Johns Hopkins University Press, Baltimore, MD, 1989, pp. 22–24.

performance capabilities (in both technical and economic terms), the coordination of payload and vehicle schedules, and assessments of the political and institutional feasibilities of chosen alternatives. Even if the latter area is neglected explicitly, it reappears in implementation planning. This assumes, of course, that one really expects the study to be implemented or have some effect other than being of academic interest. There are many motivations for a study other than direct utility, as documented elsewhere.[7]

G.2.2 Demand Projections

The most important factors affecting space transportation planning are the assumptions on the traffic demand (or "mission model") to be met. Mission models define the number, sizes, destination, and schedules of payloads to be flown. If the mission model is defined precisely enough, the required vehicles to meet it are virtually predetermined. Models can be "wish lists" of payloads without associated budgetary targets. They can be technically optimistic about the creation of advanced payloads, assume a greater demand for certain satellite services (e.g., communications), or assume growths in size and weight beyond existing launcher capabilities. Overall, mission models can assume future levels of space activity without asking the probability of or limitations to such activity occurring.

If mission models are overstated, higher development costs may be justified in the expectation that the traffic will be there to be flown. This can favor the creation of more expensive reusable systems as opposed to expendable systems which are cheaper to develop but more costly to operate. Mission models thus influence the tradeoff between recurring and nonrecurring costs for space systems.

In this study, several demand levels were defined which spanned the future range of plausible U.S. government space traffic. The demand levels did not contain detailed payload data so as to avoid vehicle-specific manifesting. Recommendations for launch vehicle mixes were made for each of the defined demand levels. The resulting recommendations were more general and robust than would have been the case if only one projection were used, due to the possible problems listed above.

G.2.3 Cost Estimates

Assumptions about the allocation and estimation of costs are another important planning factor. Serious biases can occur in defining "sunk" versus "marginal" costs.[8] Space transportation requires a large support structure of people and facilities and there is the problem of charging resources to a specific flight. One can argue that all related efforts, no matter how tenuous the link, should be charged to flights as "overhead," raising the cost per flight. One could also argue that much of the support structure would be there whether or not a specific flight occurred, thus only the marginal cost of the flight itself should be counted (e.g., propellants, crew, direct mission support, etc.).

New vehicles are often placed at a disadvantage in that their full life-cycle costs need to be justified, whereas existing vehicles have "sunk" development costs. In reaction, new vehicles may be justified on the development of new technology, operational capabilities, or for scientific reasons that do not easily succumb to cost-effectiveness arguments.

A more difficult case occurs with hybrid developments, such as the Shuttle-C, which have a high "inheritance" from earlier programs. Development costs are saved because the use of developed hardware in a new program extends the utilization of existing facilities. For

[7]Garry D. Brewer, "Where the Twain Meet: Reconciling Science and Politics in Analysis," *Policy Sciences*, Vol. 13, 1981, pp. 269–279.

[8]Marginal cost per flight is the cost of one additional flight; average cost per flight is the total cost for all flights divided by the total number of flights. Sunk costs refer to costs already incurred which are not considered in making future expenditure decisions.

example, since the shuttle will be flying fewer flights than were planned before the accident, existing external tank and solid rocket booster facilities will be used less than planned. Their support will be spread over fewer flights. Shuttle-C flights could use some of that capacity and take over some of those costs, thus ameliorating some of the shuttle cost per flight effects of the accident.

There is a danger of misusing the accounting system in hybrid systems. For example, the expendable Shuttle-C plans to use shuttle main engines already flown on 10 to 14 shuttle missions.[9] The Shuttle-C would be charged $13 million each for these "used" engines, compared to $50–60 million for a new engine.[10] This opens the question of how much shuttle costs per flight will rise under this faster "amortization" and if such increases will be accounted for in an assessment of Shuttle-C. The hybrid option can appear better in isolation than it would in a larger context.

The most basic game to play with costs is to underestimate them when getting initial new start approval. Variants on this game include holding to initial cost estimates even while the program matures and releasing revised (usually higher) estimates only after the program has been under way for some time. This allows time for political momentum to build for the program and lowers the chance of cancellation. Tradeoffs are also made with respect to total and peak-year funding requirements. Increases in the former, which are spread out over time, are often taken in preference to increases in the latter, which come at specific, potentially vulnerable times. There may thus be a tendency to hold down or stretch development costs at the expense of total program efficiency.

Cost realism was not assessed directly in this study. Official estimates for recurring costs were used for existing vehicles. Recurring and nonrecurring cost estimates were used for new vehicles such as the Shuttle-C and ALS heavy-lift vehicle. Costs for alternative launch vehicle mixes were used in selecting the best mix capable of meeting demand. Costs were not used to determine whether a new launch vehicle was economically justifiable per se.

Appendix A examined how ALS and Shuttle-C costs per flight drop as total payload traffic flown increases. As more payloads are flown, development costs and fixed recurring costs are spread over more flights and the average costs drop. Learning curve effects also help lower costs. As might be expected, it is difficult, if not impossible, to justify new launch vehicles on the grounds of saving money when compared to vehicles with sunk development costs.

G.2.4 Technical Performance

Overdesign or technical optimism is a standard problem in new programs. In space transportation, some areas are particularly vulnerable to these biases. With reusable space vehicles, such as the shuttle and potentially the National Aerospace Plane, small changes in the degree of reusability and required turnaround times can have major economic effects on life-cycle costs. In both expendable and reusable systems, designers can be optimistic about the degree of system and subsystem reliability without including the costs of ensuring such reliability in the development and maintenance programs.

A problem related to technical optimism is underestimation of required spares, logistics support, and related facilities and personnel. All new systems go through a breaking-in period as problems missed in development are found and fixed in operations. It would be foolish to assume that initial operations would have as few problems as mature operations several years or a decade later. The costs for such fixes to meet original specifications should be included in development estimates.

[9] Each SSME, three on each orbiter, was designed for 50–55 missions. To date, SSMEs are qualified for only 20 flights before major overhauls.

[10] Dale Myers, Deputy NASA Administrator, Letter to Robert Dawson, Associate Director, OMB, January 20, 1988.

Older systems may appear more attractive compared to the costs of new systems, particularly when the costs for maintaining increasingly aging systems or upgrading them to meet new, tougher operating requirements are not included. Even if development costs for current systems are considered sunk, costs are still incurred for incremental improvements to maintain a space vehicle system's usefulness.

The economic goal of ALS—lowering the cost per pound to orbit—influences the vehicle's chosen payload envelope. Low cost per pound can be achieved not only by lowering vehicle per flight costs, but by increasing the weights assumed to fly. Increasing the number of payloads can affect the mission model and the designed payload capacity. For example, the ALS is to launch a minimum of 110,000 lb to LEO. No existing payloads are 110,000 lb, so new, larger payloads must be expected (as with an SDI or space station deployment) or that multiple payloads will fly on the ALS.

Multiple manifesting on the ALS affects the types of payloads flown. Payloads go to many different locations in space, and thus some payloads will be incompatible on the same launch. Multiple manifesting also has implications for the degree of vehicle reliability. At a given reliability (say, 96 percent) one may be willing to risk a single payload, but not several payloads on the same flight. To fly several expensive payloads, the reliability may need to be higher (say, 99.9 percent). The connecting assumptions between a vehicle's payload capacity, multiple manifesting, and reliability can be overlooked, with major consequences to life-cycle costs and the scheduled payloads.

Finally, new vehicle designs such as the ALS may change the usual allocation of payload and vehicle functions. Services historically performed for payloads by the vehicle (e.g., power before and during liftoff, environmental control, and communications before separation) may be eliminated. The ALS program has supported the "flat plate" theory of payload accommodations: "here's the plate you attach your payload to and that's all you get." This "flat plate" philosophy has the effect of transferring some costs to the payload, making cost comparisons difficult for payloads flying on the ALS versus traditional vehicles. This operating philosophy does have the benefit, however, of more clearly identifying transportation costs as a separate expense.

G.2.5 Schedules

Like technical optimism, schedule optimism is a problem in any program. Space transportation must make assumptions not only about vehicle development times, but about payload development schedules as well. Historically, payloads have adapted to take advantage of new capabilities, usually growing in size, complexity, and cost.[11] Payloads take time to adapt, however, as new designs are created and validated, usually late in a vehicle's development since designers want to be sure the vehicle will be ready to go. Until then, they will hold back and design for known systems. Optimistic assumptions regarding payload availability and adaptation are often seen as necessary in justifying new vehicle designs. These assumptions then affect the mission model used for the vehicle.

Other schedule assumptions are those affecting other vehicles, which may or may not compete for the same payload market depending on when they arrive, their costs, and capabilities. A variant on this simple competition is budgetary competition. A possible competitor for the ALS was the Shuttle-C. Although both were heavy-lift vehicles, they were designed for different costs and flight rates. They were competitors nonetheless for Congressional funding until the Air Force withdrew the interim ALS proposal.

[11] "Senate tells Air Force to lose weight," *Space Business News*, May 16, 1988, p. 6.

G.3 USING THE FINDINGS

Assuming a Space Recovery Plan study has been completed, how might its findings be used? This depends to a large degree on who is interested. Congressional staff and the OMB would like to match the bureaucratic priorities of NASA and the Department of Defense with the available budgets for space transportation. Depending on the study results, they may even be convinced to increase the available budgets.

NASA and the Department of Defense could use the study results to articulate the latest "party line" or consensus as to programmatic goals and priorities. Such articulation not only helps discipline internal planning efforts, but provides an identification of the organization's values. The study can be used to identify problem areas, to claim that other potential problems are not serious, and to legitimize options that may be unknown outside the organization.

For industry, the results of government planning studies are helpful in keeping up to date on the latest positions of prospective sponsors. The studies provide insights into the relative strength of alternate sponsors, their intentions, and what priorities industry might cover in their business plans. Depending on the degree of industry input, particular companies may use study results to promote their particular launch vehicles or respond to specific threats.

A potential user of space transportation findings, the general public, has been historically neglected. The decision of President Kennedy to commit the United States to going to the moon and the debate over the creation of the space shuttle occurred without direct public debate.[12] The same is now true of the National Aerospace Plane program and the Advanced Launch System. This may reflect both a lack of public interest in space transportation per se and the technical barriers to its understanding. Whatever the reason, study results are likely to be used only within the community of individuals or organizations responsible for developing and assessing space systems.

Much of space transportation planning is sponsored by organizations who have particular goals and agendas in space operations. Thus, study results can often be characterized as persuasive analyses. Such analyses are usually effective to the degree that people are actually persuaded by them (with caveats of the many possible biases). Yet studies sometimes achieve an effect without actually persuading. Lindbloom notes:[13]

> Administrative policy makers, for example, sometimes follow the tacitly accepted rule that certain kinds of issues are to be considered settled by a competition of analyses. In effect, everyone agrees not to go further than that, that is, not to fight harder than with facts and analysis, because escalation beyond that point would demand too much time and energy and would incur too many more risks. The result is that by rule all accept certain solutions, not because actually persuaded of their merits but simple because they have agreed that the decision goes to those who have, by conventional standards, made the best case.

Certainly many technical issues are settled by analyses. For example, the assignment of government payloads to certain vehicles is a mix of technical, economic, and schedule issues, as well as political concerns. Difficulties arise when analyses are ambiguous or the stakes concern the vital interests of the organization. Examples of these points can be found in the wide range of possible mission models that can be created and how those models are tied to an organization's long-term aspirations. Whether it is "assured access to space" or "human

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[12] See John M. Logsdon, *The Decision to Go to the Moon*, University of Chicago Press, Chicago, 1970, and Scott Pace, "Engineering Design and Political Choice: The Space Shuttle 1969–1972," Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, 1982.

[13] Charles Lindbloom, *The Policy-Making Process*, Prentice-Hall, Englewood Cliffs, NJ, 1980, p. 31.

expansion into the solar system," certain policy goals are by their nature subject to simultaneously wide interpretation and passionate attachments.[14]

As the next major space launcher program being proposed by the Department of Defense, the ALS should be directly affected by a Space Recovery Program plan. The ALS program is facing at least four alternative paths. The first would proceed to the first launch of a single heavy-lift vehicle in 1996, with an IOC of 1998, and subsequent launches of large numbers of payloads taken over from other ELVs. Another path would create a number of vehicles, allowing for a variety of sizes, based on a common core development program. A third path would take the technology program planned in any case and adapt its results in an incremental upgrading of existing ELVs. This option could also be called a successful ALS program if the net result was to provide a lower cost, more reliable means of access to space. Finally, the ALS effort could be cancelled entirely due to an unexpected technological breakthrough, restrictive DoD budgets, or a judgment that existing vehicles are adequate.

Space transportation study results that would redirect the ALS program are likely to be the required budgets, the adequacy of current systems compared to future requirements, and the credibility of those requirements. However, many subtle and not so subtle biases can be introduced into planning studies. Users of space transportation planning studies must be alert to the potential biases of the study sponsors while assessing the plausibility of the final recommendations. This requires political sensitivity, a knowledge of resource constraints and current capabilities, and an awareness of the space policy options that will ultimately drive space transportation requirements.

[14]These goals for DoD and NASA, respectively, are from the latest articulation of national space policy, NSDD 293. See The White House, "Presidential Directive on National Space Policy—Fact Sheet," Office of the Press Secretary, Washington, D.C., February 11, 1988.

Appendix H
CHRONOLOGY THROUGH 1988

1981	
04/12/81	First launch of the space shuttle.
1982	
07/04/82	National Space Policy statement based on NSDD-42 released. The space shuttle is the "primary space launch system for both United States national security and civil government missions."
1983	
05/16/83	NSDD 94 endorses the commercialization of U.S. expendable launch vehicles.
1984	
01/25/84	President Reagan, in his State of the Union address, calls for the development of a permanently occupied space station within a decade.
1985	
02/25/85	NSDD 144, the National Space Strategy, directs the DoD to procure ELVs to complement the STS. These become the Titan 4s built by Martin Marietta.
05/01/85	NSDD 164 directs NASA and DoD to conduct a joint study of space transportation architectures for the 1995–2010 time frame.
08/28/85	Destruction of a Titan 34D during launch.
10/01/85	Contracts are awarded to Rockwell, General Dynamics, Boeing, and Martin Marietta to support the National Space Transportation Strategy Study (see NSDD 164).
1986	
01/01/86	Air Force Systems Command announces the creation of a National Aerospace Plane Program office.
01/28/86	Space shuttle Challenger destroyed during lift-off. Remaining shuttles are grounded.
02/04/86	President Reagan endorses the creation of a National Aerospace Plane (NASP) in his State of the Union Address.
04/18/86	Destruction of a Titan 34D during launch. Titan fleet grounded.
05/01/86	Mid-term reports of the National Space Transportation and Support Study 1995–2010 released. Also known as the Space Transportation Architecture or STAS studies. Contract extensions granted to look at some issues in more detail.

05/03/86	Delta launch vehicle destroyed during liftoff.
06/01/86	Senator Sasser (D-TN) of the Subcommittee on Military Construction issues report on the shuttle launch facilities at Vandenberg AFB.
06/06/86	Rogers Commission releases its final report on the loss of the shuttle Challenger.
06/17/86	First NASA release of a post-accident flight schedule.
07/22/86	The National Commission on Space submits its report on long-term goals for the U.S. civilian space program.
08/15/86	President Reagan announces the decision to build a replacement shuttle orbiter and to limit the use of the STS to shuttle-unique payloads, moving almost all commercial payloads to ELVs.
09/05/86	Return to flight of Delta launch vehicle.
10/01/86	Congressional Budget Office releases its report on "Setting Space Transportation Policy for the 1990s."
10/01/86	National Research Council releases its report on "Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization."
10/31/86	General Accounting Office issues report on the Vandenberg AFB shuttle launch site.

1987

01/01/87	Air Force awards contract to McDonnell Douglas for Delta 2s to serve as medium launch vehicles (MLV 1s) primarily for the Navstar program.
03/10/87	Department of Defense Space Policy released.
03/26/87	Atlas-Centaur destroyed on liftoff by lightning strike.
05/01/87	Advanced Launch System Phase I Request for Proposals released.
07/10/87	Phase I ALS contracts ($5 million each) awarded to Boeing, General Dynamics, Hughes, Martin Marietta, McDonnell Douglas, Rockwell, and USBI Booster Production (a division of United Technologies).
07/13/87	Atlas-Centaur damaged beyond repair by launch pad processing accident.
07/21/87	STAS contractors briefed on new mission models for the Civil Space Leadership Initiatives. These models covered lunar bases and manned Mars missions.
08/03/87	First refurbished Titan 2 launchers produced.

09/01/87	Report by Sally Ride on U.S. space leadership released by NASA.
10/01/87	Rockwell, General Dynamics, and McDonnell Douglas selected for further NASP development efforts.
10/05/87	Air Force announces plans for a second medium launch vehicle (MLV 2) for defense communications satellites.
10/21/87	NASA issues first mixed-fleet manifest since the loss of STS 51-L (Challenger).
10/26/87	Return to flight of the Titan 34D launch vehicle.
11/01/87	Three parallel definition studies awarded by NASA for a shuttle-derived cargo vehicle, or Shuttle-C.
11/17/87	ALS launch cost goal of $300/lb attached to House DoD Appropriations bill.
11/25/87	NASA (Dale Myers) and DoD (Lt. Gen. Abrahamson) agree to draft management plan for the Advanced Launch System.
11/30/87	Space Transportation Architecture (STAS) studies completed.
12/04/87	Congress withholds ALS funding pending Air Force/NASA final agreement on program management. Contractors issued stop-work orders.

1988

01/04/88	Report of joint management plan for the ALS signed by President Reagan and sent to Congress.
01/14/88	First Titan 4 arrives at Cape Canaveral.
01/11/88	Requests for Proposals for a Medium Launch Vehicle 2 released by the Air Force.
02/02/88	Office of Technology Assessment reviews its draft report on future space transportation architecture options.
02/11/88	President Reagan announces a new U.S. space policy, based on NSDD 293. Stresses the use of a mixed fleet of the STS and unmanned launch vehicles. "Payloads will be distributed . . . to minimize the impact of loss of any single launch system . . . on mission performance."
02/15/88	Meetings at USAF Space Command to revise upcoming ALS Request for Proposals. Revisions reflect a "philosophy on a family of vehicles, and the spinoff of technologies to existing and future boosters."
03/01/88	Revised NASA and DoD launch manifest released.

03/18/88	Air Force and Sen. Stennis (D-MS) of the Senate Appropriations Committee agree on funds for the ALS and propulsion testing work at the National Space Technology Labs in Mississippi.
03/19/88	Phase I Shuttle-C contract funds depleted. Office of Management and Budget opposes NASA requests to reprogram funds for Phase II studies.
03/21/88	ALS Phase I contracts restarted.
04/01/88	Phase I Shuttle-C contracts completed.
04/20/88	Advanced Launch System Phase II Request for Proposals released.
04/24/88	Air Force announces that West Coast shuttle launch facilities at Vandenberg AFB are to be mothballed.
04/25/88	ALS Phase I mid-term reviews.
05/03/88	General Dynamics selected as contractor for MLV 2 program.
06/27/88	Department of Transportation releases first commercial space launch manifest.
07/27/88	Release of *Launch Options for the Future: A Buyer's Guide* by the Congressional Office of Technology Assessment.
08/16/88	ALS Phase II contracts awarded to a Martin Marietta-McDonnell Douglas team, Boeing, and General Dynamics.
09/02/88	Third successful Titan 34D launch since the April 1, 1986 explosion. Upper stage failed, however.
09/05/88	First launch of refurbished Titan 2.
09/29/88	Shuttle return to flight with launch of STS-26.
11/31/88	Second shuttle mission with STS-27.
12/06/88	Kick-off meeting on Assured Space Support Architecture study at U.S. Space Command.
Future	
1989	First launch of Titan 4. First launch of MLV 1 First launches of commercial Delta, Atlas, and Titan.
1991	First launch of MLV 2.
1992	Shuttle backlog from January 1986 accident eliminated.

1994	First launch of space station components. First flight of Shuttle-C?
1995	First flight of an X-30 National Aerospace Plane?
1996	First launch of an Advanced Launch System vehicle?
1998	Initial launch capability for the Advanced Launch System? X-30 demonstrates single-stage to orbit?

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